An agent-based model for vegetation development in the floodplains

Master thesis

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Summary

Due to climate change the discharge in the rivers is expected to change, which will affect water level in the rivers and the flood frequency of the floodplains. This could also have a large impact on vegetation development in the floodplains. To investigate the impact of varying water levels on the vegetation, a prototype for an agent-based model has been created.

There are three major components that influence vegetation development in the floodplains: succession, floods and interventions, like removing vegetation as is currently done by Rijkswaterstaat. Based on these factors the model has been divided in a vegetation sub-model, a flood sub-model and an intervention sub-model.

In the vegetation model, vegetation is divided into eight vegetation types. Each raster cell has data on the percentage of each vegetation type that is present in that cell. Ecological succession transforms vegetation from one type to another. This is represented in the model as a change in percentage of vegetation type. The direction of this change as well as the rate of this change is dependent on the flood frequency and human interventions. As a result, vegetation development varies per location.

A pre-existing flood model, developed by Benninga (2013) was used to simulate floods. In this model the monthly changing water level data is subtracted from the elevation data. If the water level is higher than the local elevation, the area is inundated. Depending on other factors, such as vegetation type, flood depth and season, vegetation might be removed by the inundation.

In the intervention model, the Rijkswaterstaat agent compares the vegetation in the model to the norms in the Vegetatielegger. The Vegetatielegger is a set of norms on a map for vegetation in the floodplains made by Rijkswaterstaat. If it is expected that an area will not be inundated next spring and it also exceeds the norm, the Rijkswaterstaat agent intervenes and removes certain vegetation types, depending on the norm.

Following the integration of the three sub-models, the entire model was tested in a sensitivity analysis and in multiple scenarios. One of the results of the sensitivity analysis was that decreasing the water level had a larger impact on flood frequency than increasing it, while roughness was more affected by an increase in the water level.

The scenarios demonstrated that lowering the intervention frequency does not necessarily lead to a large increase in roughness. In contrast, intervention did have a large influence on the total grass cover in the research area as a high intervention frequency led to a significantly higher grass percentage. Floods had a similar effect on the bare soil class.

Due to the lack of other vegetation datasets with numerical values, it was impossible to validate the model properly. More numerical data can also make it possible to integrate more factors in the model and balance the impact of floods further. This could lead to improvements of the model.

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1. Introduction

1.1. Problem description

Managing river discharge is an important component of water management in the Netherlands as it is a way to protect the country from potential floods. To keep the amount of water manageable, various measures have been taken, such as constructing dykes and increasing the depth of the rivers and creating side channels (Brandsma, 2016). However, due to climate change the discharge and the water level in the rivers are expected to change (Kwadijk & Middelkoop, 1994).

A change in the water level of rivers, either an increase or decrease affects the vegetation in the floodplains. The water level of the rivers has a large effect on vegetation, because plants can be sensitive to floods. Information on vegetation in the floodplains is important to Rijkswaterstaat, because vegetation influences the amount of water that can flow through a riverbed and its floodplains. The capacity of the riverbed and its floodplains is measured in hydraulic roughness. Larger plants, such as trees, increase the roughness more than grasses and other smaller plants. A river with a high hydraulic roughness can transport less water and has a higher flood risk than a river with a low roughness (Peters, 2002).

Vegetation also changes over time because of changing environmental conditions, ecological succession and human influences. Every plant species has its own environmental preferences, which allows them to have advantages over other species in the same area. When the conditions of an area change, the vegetation might also change. Environmental conditions affect the distribution of vegetation as a result. Floods are an example of an environmental condition in the floodplains. Some plant species are more tolerant to inundation than others and will be able to endure floods for a longer time (Hughes, 1997).

Vegetation itself can be seen as an environmental condition as well, because it has an influence on which other plant species can grow in the same area. For example, trees can cast shades over other plants, limiting the amount of sunlight in the area. In this area shade tolerant plants will have an advantage over plants that require direct sunlight (Gurnell et al,. 2016). The impact of vegetation on other plant species in combination with regularly occurring floods causes vegetation development to progress in a certain order. Since environmental circumstance differ from area to area, the exact order of vegetation development can be completely different in one place compared to another (Peters, 2002).

Figure 1-1 depicts an example of how vegetation could develop. Pioneer vegetation is substituted by grass over time. In the first step of this example, bare soil shift into pioneer vegetation. After some time, areas with grass develop into areas with herbs. These herbs will eventually be replaced by shrubs, which in turn will be succeeded by trees. This process of changes in vegetation is called ecological succession (Peters, 2002). This is only a simple example to give an impression of ecological succession and does not include all the possible directions in ecological succession. More complex depictions of succession, such as the succession matrix of Peters (2002), will be covered in chapter 2.

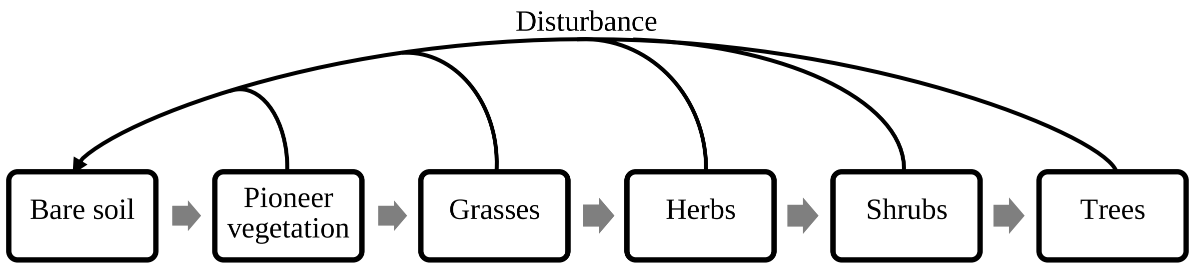

Figure 1-1: An example of vegetation development.

Ecological succession is affected by so-called disturbance factors. Disturbance factors are events that influence the succession process by destroying existing vegetation or slowing down its progression. If vegetation is destroyed by a disturbance, the ecological succession process starts all over. A disturbance can occur at any step of the succession process. A disturbance can be caused by natural events, such as fires or floods, or by humans actions, such as deforestation and canal construction, or by animal activities like grazing or trampling the vegetation (Baptist et al., 2004; Peters, 2002).

Human actions also influence the development of vegetation in other ways. The land use of the floodplains has a large impact on how ecological succession exactly progresses. For example, ecological succession will advance slower in grasslands that have been fertilized, than in grasslands without fertilization. Another way human actions influence vegetation development is through the Cyclic Floodplain Rejuvenation (CFR) strategy. For this strategy floodplains are lowered and trees are removed to reduce the hydraulic roughness. The goal of the CFR strategy is to lower flood risk and to increase biodiversity in the floodplains (Baptist et al., 2004; Peters, 2002).

Agent-based models are effective tools to model environmental changes and the ecological processes described earlier. Furthermore, agent-based models are usable for both exploratory and predictive research (Braun & Rosner, 2011). They allow for integrating environmental processes with agent behaviour. This is useful when modelling human intervention strategies and disturbances. Several agent-based models of vegetation development exist but most models focus only on vegetation succession and not on the interaction between flooding, vegetation and human interventions. A model that includes these elements can help improve the understanding of these interactions.

1.2. Relevance

This research is linked to the research programme RiverCare. This research programme is a cooperation between various public and private parties with the Netherlands Centre of River Studies (NCR), which is a network of research institutes. Together these parties investigate the consequences of two Dutch water management programmes: Room for the River and the Delta Programme. The goals of RiverCare are to increase the knowledge of the behaviour of rivers, map the impact of the measures taken in the two programmes on hydrology, morphology, and ecology and to improve existing models.

By creating the flood and vegetation models this research assists the RiverCare programme (NCR, 2017). These models could help to map the impact of the measures of the two programmes and improve existing models.

An integrated model on vegetation development, flooding and human intervention could also help Rijkswaterstaat to evaluate the impact of changes in the water level on vegetation development. These predictions could help lower the need to monitor the vegetation. These predictions can aid Rijkswaterstaat in protecting the Netherlands against floods, which makes this research relevant for society.

Furthermore, this research is scientifically relevant as well. Only a limited number of agent-based models have been developed for ecological succession, such as the models of Braun & Rosner (2011) or Spies et al. (2017). These models focus on ecological succession in mountains after deforestation and in forest after wildfires respectively. They do not combine ecological succession with floods, nor do they cover floodplains in lowland rivers.

1.3. Objectives

The goal of this research is:

To develop an agent-based model for vegetation development in river floodplains in order to determine the impact of changing water levels on vegetation management.

Based on the previous sections, it is expected that vegetation succession and floods will play an significant role in this model.
To achieve the goal of this research, the following main research question has been formed:

1. *How can an agent-based model be created that can be used to evaluate the impact of changing water levels on the vegetation development in river floodplains and its management?*

This question can be divided into four parts, one part covering the creation of a vegetation model (1), one covering flood models (2) and another covering the modelling of human interventions (3). The final group of research questions relate to the integrated model (4).

1. For the creation of the vegetation model the following research questions were defined:

    1.1. *What factors influence vegetation development in the floodplains?*
    1.2. *What models on vegetation development currently exist?*
    1.3. *How can the factors that influence the development of vegetation be integrated in an agent-based model?*
    1.4. *How can the vegetation model be calibrated?*

2. For the creation of the flood model, the following research questions were defined:

    2.1. *What flood models currently exist?*
    2.2. *What existing flood model is appropriate to use in combination with the vegetation model?*
    2.3. *How can the models of vegetation development and floods be integrated into one model?*
    2.4. *How can the flood model be calibrated?*

3. For modelling the interventions/disturbances the following research questions have been defined:

3.1. Which interventions need to be modelled?
3.2. How can interventions in the floodplains be included in the vegetation model?
3.3. How can interventions be calibrated?

4. The following research questions have been defined for the integrated model:

4.1. How sensitive is the model to changes in model parameters?
4.2. What are the effects of changing combinations of parameters?

1.4. Limitations

Only one area in the Dutch floodplains is chosen as the research area, because the total size of floodplains in the Netherlands is far too large to model completely in an agent-based model. The chosen research area is the Duursche Waarden. This is a natural area adjacent to the river the IJssel in the Netherlands in the province of Overijssel between the town of Olst and Wijhe. The research area is approximately 133 hectares with only limited human influence (Dirks et al. 2014). Figure 1-2 shows the extent of the research area and its vegetation. The map only displays the largest vegetation group for each area.

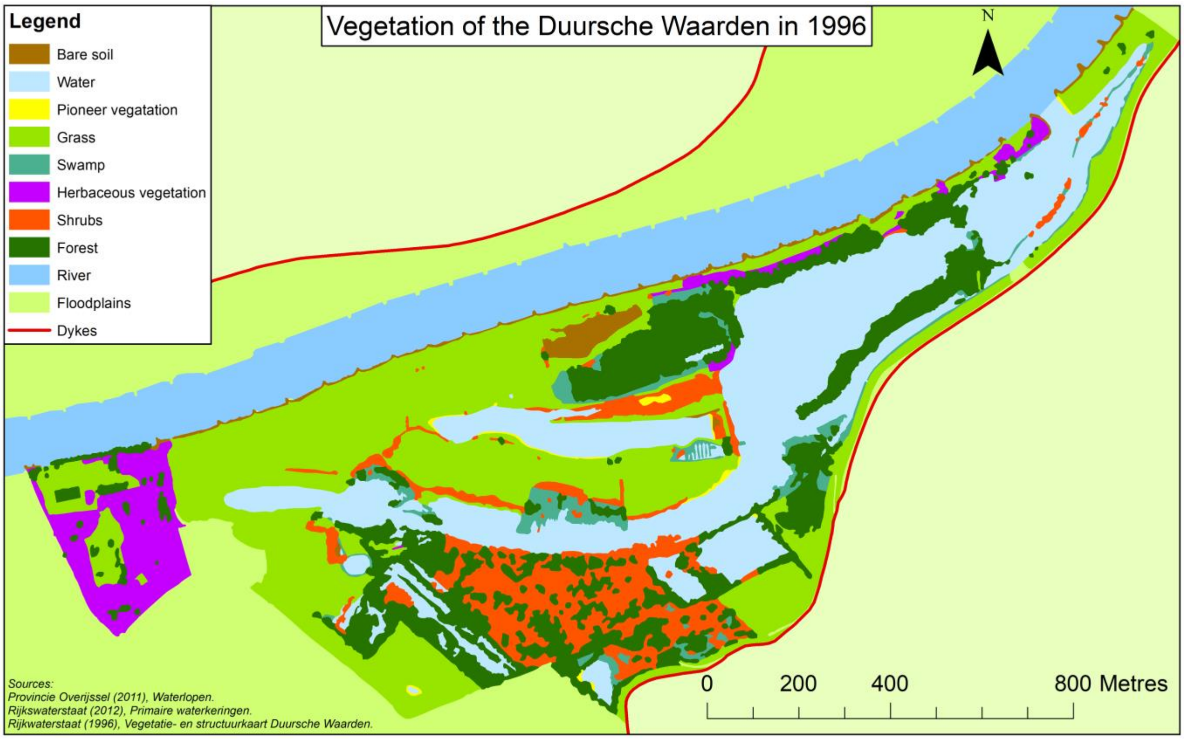

Figure 2-2: Vegetation of the Duursche Waarden in 1996.

As a second limitation, no new flood model will be created for this area. Instead an existing flood model will be chosen, which is generic and therefore less tuned to the specific situation of the study area. The output of this flood model will be integrated with the vegetation model.

Another limitation is that the model will not simulate all vegetation species individually. The different plant species will be grouped into vegetation types. As a result, changes within one of those vegetation groups might not be visible in the model. The model will for example not display a change from one grass type to another.

A final limitation is that a model will not take all possible factors into account, but only the most influential ones. A model should be as simple as possible for multiple reasons. A limited number of variables will make the model easier to understand and calibrate, the computations faster and the required amount of data smaller (Helbing, 2012). Moreover, there is not enough data available for some of the factors to include these in the model.

1.5. Approach

The research has the following setup:

1. Literature review
    a. Vegetation development
    b. Vegetation models
    c. Flood models
    d. Interventions
2. Design and implementation of the model
    a. Choosing a flood model
    b. Vegetation and intervention sub-model design
    c. Data collection and preparation
    d. Vegetation model development
    e. Intervention model development
    f. Integration of the three sub-models
3. Testing the model
    a. Robustness test
    b. Sensitivity analysis
    c. Scenarios

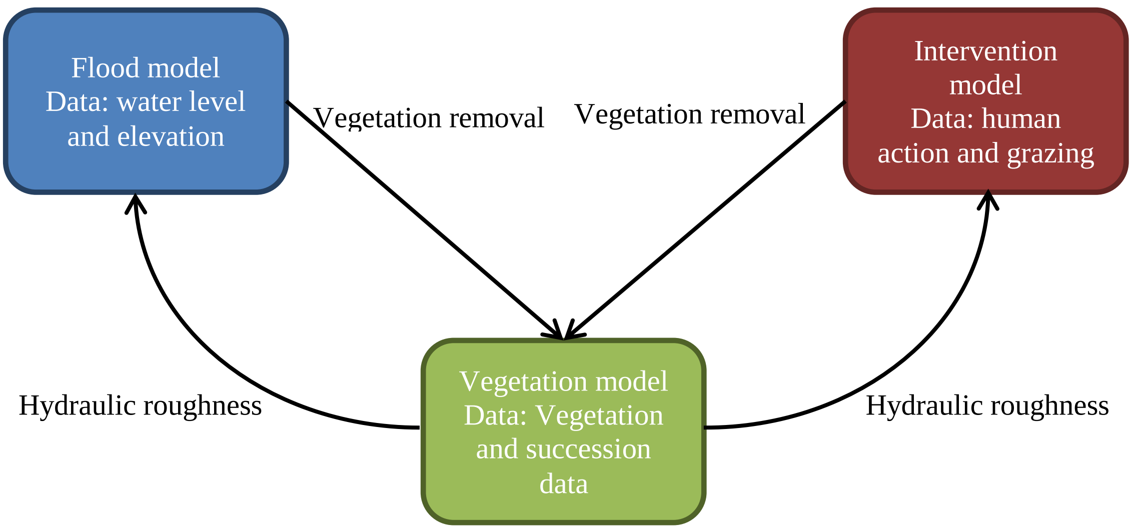

Figure 1-3: Sub-models and information flow (feedbacks) between these models and the required data input for each sub-model.

The final model can be split up into three smaller sub-models: a flood model, a vegetation development model and an intervention model for grazing and human actions in the floodplains. As depicted in figure 1-3, the models for flood and intervention models serve as input for the vegetation model. Floods and interventions influence vegetation development through vegetation removal. However, vegetation development also affects the flood model, as vegetation with a higher hydraulic roughness reduce water flow velocity and increase water depth. The intervention model is also affected by vegetation development, because areas with too much roughness have a high flood risk. In these areas interventions are necessary to reduce the flood risk. Consequently, the output of the vegetation model can also be used as input for the flood and intervention model. The downside of using an existing flood model is that it is not possible to integrate the effect of vegetation on floods.

1.5.1. Vegetation model

To answer the first sub-question (Q 1.1) a literature study is required on vegetation development in floodplains. For this research question, the environmental characteristics that influence the development of vegetation are investigated. This literature study should give an overview of how vegetation in floodplains generally develops. These are factors that alter the rate of vegetation development or change the outcome of the development of vegetation. The goal of this literature study is not only to gain a better understanding in the elements that influence vegetation development, but also to serve as input for the model. A part of this sub-question and the literature study is the creation of a conceptual model for vegetation development.

More literature study will be done for the second research sub-question (Q 1.2). To answer this question, existing models on vegetation development will be investigated. There are only a limited number of examples of agent-based models for vegetation succession available, including the models of Braun and Rosner (2011) and Spies et al. (2017). Consequently, other models that are not agent-based will be included in the literature study, such as the models of Baptist et al. (2004) and Millington et al. (2009). Examining vegetation models that are not covering floodplains will be part of this research question for similar reasons. These models will function as examples for the final model.

After the literature study on vegetation development and the creation of a conceptual model, the information from the first sub-question (Q 1.1) must be converted to factors that can be used in an agent-based model. This can be supported by using the examples that result from the second sub-question (Q 1.2). The result should answer the third sub-question (Q 1.3).

1.5.2. Flood model

The vegetation model also requires a flood model as input, because floods play a major role in vegetation development by influencing ecological succession as a disturbance. The required flood model is covered by the second set of sub-questions.

Similar to the vegetation model, the existing flood models will be examined (Q 2.1). This can be used to determine advantages and disadvantages of certain models and to determine which existing flood model is best suited to be integrated with the vegetation development model. Investigating these models answers the first sub-question of the flood model and will also be part of the literature study. Both agent-based models and other flood models will be studied to determine the most suitable model.

For the second sub-question (Q 2.2) on flood models, the information of the previous sub-questions will be used to decide what flood model is most suited for this research. This sub-model should be able to predict floods with the current and altered water distributions.

To answer the final sub-question on flood models (Q 2.3), the flood model will be combined with the vegetation model. It is likely that this sub-question will be answered gradually during the creation of both models. The combination of both models should give an answer to the main research question.

1.5.1. Intervention model

To answer the first sub-question on interventions (Q 3.1), a literature study will be done on the interventions in the floodplains. This covers the most important disturbances that are not related floods, such as grazing.

These disturbances are implemented in the intervention sub-model for the second research sub-question (Q 3.2). Combining the intervention sub-model with the vegetation model is also part of this question.

1.5.2. Sensitivity analysis and scenarios

For the final pair of sub-questions the model, created with the answers on all the previous sub-question, will be answered. This is done by performing a sensitivity analysis (Q 4.1) and by examining various scenarios (Q 4.2).

2. Literature review

In this chapter the literature on vegetation development and floods will be discussed. First, the factors in vegetation development in the floodplains are covered. This is followed by a discussion on various vegetation models. Both agent-based vegetation models and other vegetation models are covered. At the end of the chapter, a number of flood models are examined.

2.1. Vegetation development in floodplains

2.1.1. Succession

Ecological succession was already briefly explained in the introduction. Over time, vegetation develops from one species to another. As said in the introduction, the exact development path is highly dependent on the location and its features. Peters (2002) distinguishes ten succession paths in the river floodplains in his succession matrix. This succession matrix does not only show how vegetation develops over time from varying starting situations, but also includes percentages of the vegetation composition of the states in the matrix.

One of the key components in these paths is elevation. Elevation in the succession paths is not measured in meters above sea level, but in the amount of days with inundation per year. This is used to divide the succession paths in three elevation levels: low, middle and high. The middle and high elevation level contain three succession paths, while the low elevation level consists of four paths.

The succession paths in the matrix are further defined by their starting situation. Grassland has for example a different path than the riverbanks. For all three elevation levels, one path covers the succession of grassland and one path displays the development of former agricultural fields. The starting situation of the remaining succession paths varies per elevation level.

The succession matrix of Peters (2002) is based on a few assumptions:

- Regressive (backward) succession is not included. This means that in the succession matrix disturbance factors do not have any effect on the vegetation. Any decrease of vegetation is caused by ecological succession itself.
- The course of the river is static.
- It is assumed that there is natural grazing.
- There is spontaneous succession. This implies that there are no human influences that steer vegetation development to a certain state.
- The numbers in the succession matrix are based on expert-judgements specifically done for the Dutch Rhine and Waal areas.

Van Velzen et al. (2003) have created succession schemes with similarities and differences to the succession matrix of Peters (2002). Ecological succession in these schemes is dependent on the wetness of the area, which is similar to the elevation levels used in the succession matrix. However, there are only two succession schemes: one for the lower wetter areas and one for the higher and dryer areas.

Another difference is that the succession schemes of Van Velzen et al. (2003) do include disturbance factors. Furthermore, there is no differentiation between the starting situations in the succession schemes, as was done in the succession matrix. The succession schemes also lack the percentages of the vegetation composition. Instead, the schemes show in what direction vegetation can develop on either low or high elevation.

2.1.2. Starting situation

The land use of the starting situation in an area is also of significance in ecological succession. Peters (2002) describes three possible starting situations of land use in this process in the floodplains of the Netherlands, which are all results of human activity: grasslands, agricultural fields and recently created secondary channels.

For grasslands and agricultural fields a distinction is made between dryer grasslands that only experience floods in the winter and wetter grasslands that can also be flooded in the summer. In the relatively dry grasslands ecological succession progresses relatively slowly. Since grass leaves little empty spaces, there is not enough room for other species to grow. However, after some time more empty spaces are generated, because the nutrients in the soil have diminished. This is caused by the leaching of nutrients and by grazing animals. The animals can also create empty spaces within the vegetation by eating or trampling the vegetation. In the dryer agricultural fields the development of vegetation starts with fast growing herbs. These herbs are quickly followed by shrubs. Similar to grasslands, open spaces are created over time. The reasons for this increase are the limited lifespan of herbs and grazing animals. The empty spaces between the grass and herbs allow other species to grow, such as shrubs and trees. Open spaces will appear faster on gravel, sand and loam than on clay. However, the appearance of open space will be slowed down if a lot of nutrients are present in the soil (Peters, 2002).

In the lower wetter grasslands of the floodplains, ecological succession proceeds at a faster rate. Due to a higher frequency and duration of flooding the soil moisture increases and more silt is being deposited in the lower areas. As a result, the grasslands become more open. These factors can lead to a greater diversity of grasses and enables the growth of trees. In the wetter agricultural lands succession is very similar to that of the dryer fields. The main difference is that these areas also support the growth of trees, shrubs and marsh plants (Peters, 2002).

The development of vegetation on the banks of the recently constructed secondary channels depends on multiple factors, including the hydrology, soil type and grazing intensity. On wet clay soils, willows create a dense forest. In the dryer areas other tree types can be found as well. In areas that that are inundated too often for trees, amphibian species can grow during the summer. Moist sand areas are suitable for forests as well, however dryer areas are generally covered by herbaceous vegetation. Gravel can soil also support trees, provided the soil has enough moisture. The chance that trees will grow on this soil type is increased if it is mixed with other soil types, such as silt or loam (Peters, 2002).

2.1.3. Ecotopes

Since there is such a high number of different plant species, it can be useful to aggregate these species in larger groups. As was explained in the introduction, Rijkswaterstaat has defined ecotopes to help manage water systems, including rivers. Officially the system of ecotopes is called RijksWateren-EcotopenStelsel (RWES). The RWES used to consist of five distinct water systems: rivers, lakes, lower rivers, channels and salty waters. However, this division has been changed and currently RWES consists out of three groups: aquatic ecotopes, bank ecotopes and terrestrial ecotopes. The floodplains mostly fall under the terrestrial group. In total, 28 terrestrial ecotopes have been defined by Rijkswaterstaat (Willems et al., 2007).

Ecotopes are based on conditional factors, which are related to the proximity of the river. Willems et al. (2007) distinguish three conditional factors: morphodynamic factors, hydrodynamic factors and usage dynamic factors.

- Morphodynamic factors are mechanisms that influence the soil, vegetation and wildlife of an ecotope. This includes factors such as erosion, sedimentation and waves.
- Hydrodynamic factors are the effects of the water table and flow velocity on soil, vegetation and wildlife.
- Usage dynamic factors are deliberate human actions that have an impact on soil, vegetation and wildlife.

The 28 ecotopes are divided in three distinct zones that are based on the location: the riverbanks, the high floodplains and the flood free zone. The riverbank ecotopes originate from the deposition of sand by rivers, which occurs at the upper parts of the Dutch parts of the Rhine and Meuse, mostly at the inner bends of the rivers. Morphodynamic factors have a large effect on these ecotopes, especially through sedimentation. The impact of sedimentation is even more significant during high water. Hydrodynamic factors can have a significant impact on the riverbanks as well, as these areas can be inundated up to 50 days a year (Willems et al, 2007).

The high floodplains are located next to the rivers in the areas that are highly affected by the river. The main difference with riverbank ecotopes is that the morphodynamic factors are less influential in the high floodplain ecotopes (Willems et al., 2007).
The flood free zone is the zone with the least influence from open waters. Morphodynamic and hydrodynamic factors have a limited impact on the ecotopes in this zone. The flood free zone is not only used for rivers, but for all waters that are administered by Rijkswaterstaat (Willems et al. 2007).

While ecotopes are useful for creating a better understanding of vegetation development, there is a problem with translating ectopes into a model; it is difficult to model gradual changes within ecotopes. However, ecotopes are the basis of the succession matrix of Peters (2002). Therefore, ecotopes are useful for understanding the succession matrix.

2.1.4. Impact of floods

River floods are an example of a disturbance in the ecological succession process and are therefore significant factors in vegetation development. While submerged, plants are often derived from oxygen, which they require to survive. The impact of floods on vegetation therefore depends on a number of factors, including: vegetation type, the timing of floods, flood depth and flood duration (Glenz et al., 2006).

Depending on the vegetation species, inundation can damage plants, prevent the creation of seeds, alter the plant anatomy and lead to an earlier death. Some vegetation types can last longer in an inundated state. The ability of vegetation to survive longer while inundated is called flooding tolerance. Due to the difference in flooding tolerance between vegetation species, the more tolerant species are able to grow at lower heights closer to the river (Glenz et al., 2006).

The timing of floods is one of the most important factors in the impact of floods. During the largest part of the year, most plants are in a dormant state. While in this state, they are less active and require therefore less oxygen. Even longer flood durations only have a minimal impact, while the plants remain in a dormant state. As a result, the plants are more resistant to floods. However, in the growing season a lot more resources are spent on growth and reproduction. This makes the plants more vulnerable to the impact of inundation (Glenz et al., 2006).

Flood damage is also dependent on the flood depth, because soil inundation does not have the same effect as complete submersion. The submersion of foliage in particular increases the flood damage significantly. As a result, taller vegetation types are more likely to survive a flood than smaller ones (Glenz et al., 2006).

The longer a flood lasts, the higher the chance that vegetation will be damaged. Particularly during the growing season, flood duration is an important factor in the effect of floods. Even woody vegetation types with high flood tolerance need to be unsubmerged at least 60% of the growing season (Glenz et al., 2006).

2.1.5. Interventions

Human interventions can be significant disturbances in ecological succession as well. Since the area of the Duursche Waarden is designated as a natural area, human interventions are limited. However, because the Duursche Waarden are located next to a major river, occasional interventions are required. Generally, if vegetation is left unchecked, the hydraulic roughness of an area will increase, because ecological succession replaces low roughness plants with rougher vegetation types. As was explained in the introduction, a higher hydraulic roughness increases the flood risk. Therefore Rijkswaterstaat intervenes by removing vegetation in the floodplains to reduce the hydraulic roughness (Rijkswaterstaat, 2014).

To regulate the removal of plants, norms for vegetation have been set. These norms dictate the allowed amount of vegetation and roughness in the floodplains. The norms vary per area and are based on the existing vegetation in 2014. There are two types of norm classes: homogeneous classes and mixed classes (Rijkswaterstaat, 2014).

In areas with a homogenous norm, the entire area has a certain vegetation type as limit. Only that vegetation types with the same roughness or less are allowed to grow in those areas. For example, in an area with the reeds and herbs norm, both herbs and grasses are allowed to grow. Trees and shrubs on the other hand, need to be removed (Rijkswaterstaat, 2014).

The mixed norm classes also permit the growth of vegetation with less roughness. The difference is that with the mixed vegetation norm certain vegetation types are allowed to grow a certain size. These sizes are measured in percentages with a minimum set to grass and a maximum to forests and shrubs. For example, the 70/30 mixed norm class signifies that at least 30% of areas with that norm have to be grass or fields, while a maximum of 40% is allowed to be forest and shrubs. The full list of norms and their implications for the model will be discussed in section 4.4 (Rijkswaterstaat, 2014).

When these norms are exceeded, vegetation is removed by Rijkswaterstaat. The norms also apply to privately owned land in the floodplains. The landowners are consulted when interventions in their property are necessary (Rijkswaterstaat, 2014).

2.1.6. Grazing

According to Gibson and Brown (1992), grazing animals can deflect succession. This means that the succession process is halted at its current stage. However, this is highly dependent on the pace of the succession process. When grazing is stopped, ecological succession will continue and the same climax vegetation will be reached as without grazing. Grazing can only alter the outcome of succession under extremely high grazing intensities.

2.2. Models

2.2.1. Agent-based vegetation models

Braun & Rosner (2011) have described how vegetation succession can be modelled by using agent-based modelling consisting of environments and agents. In this model the agents represent only the seeds of plants, while the patches contain information on land cover and other factors that are required for the simulation. The disturbance factor in this model is deforestation, which has occurred before the start of the simulation. Further potential deforestation is not included in the model, which means that the disturbance factor in this model is static. Other factors in the model that influence succession are static as well.

The model follows a couple of rules:

- Some vegetation types require the presence of other vegetation types to be able to grow on a certain cell (e.g.: woodland can only grow on cells with shrubland)
- Seeds are more likely to spread downhill than uphill and will also spread faster downhill.
- Grass is more tolerant to sunlight, while shrubland and woodland will grow faster in areas with shade.
- The climax stage of succession can differ per location and is dependent on the elevation.

In the model, the seed agents start to move at the edge of the deforested area. The movement speed and direction of these agents is dependent on the elevation of the surrounding cells and the amount of sunlight and the tolerance of sunlight of the seed type.
Besides the initial bare soil stage, the cells in the model can be in one of three vegetation stages: grassland, shrubland and woodland. The progression of vegetation development is modelled in a decision tree. In this tree, bare soil can only change into grassland, which in turn can only develop into shrubland or remain grassland. The outcome after shrubland can vary between transforming into one of five classes of woodland or remaining as shrubland. The climax stage of a cell is dependent on a spatial analysis on what outcomes are plausible based on the elevation. As a result some cells might not end up as woodland, but as grassland or shrubland (Braun & Rosner, 2011).

A different agent-based model on vegetation succession was developed by Spies et al. (2017). In this model forest fires are the disturbing factor in the succession process, which is modelled by using data on vegetation, topography and weather. The model is an integration of three smaller models, similar to figure 1-2: a forest succession model, a wildfire model and a forest management model. The agents in this model are the major land-owners, who influence the occurrence of wildfires and forest succession by forest management activities. The decisions made by these agents are based on econometric models and targets, constraints and preferences of landowners. Succession and wildfires can also affect the choices made by the agents (Spies et al., 2017). A similar method could be used to incorporate the actions of Rijkswaterstaat and landowners in the floodplains in the model for this research.

The vegetation sub-model is based on state-and-transition models, which is used in other models of vegetation development as well. A state, or class, in these types of models is a combination of the vegetation type and its structure. A state-and-transition model consists of multiple of these states, which are linked by transitions. Transitions describe under what conditions vegetation can change into a different state. These transitions can occur when there are disturbances or when vegetation has developed and other plant species become dominant (Burcsu et al., 2014; McIntosh et al., 2003). Succession occurs when a plant species reaches a specific maximum age, which is the deterministic part of the model of Spies et al. (2017). However, during each time step, probabilistic transitions can occur within the model as well, resulting in different succession paths. For example, the effect of wildlife on vegetation can be modelled as probabilistic. However, some transitions can only occur after a certain amount of time since the previous transition or disturbance (Spies et al.,2017).

2.2.2. Other vegetation models

Millington et al. (2009) also use the state-and-transition models as basis for simulating vegetation succession and the impact of wildfires. This model is partly based on a proof of concept created by McIntosh et al. (2003), called Rule-Based Community-Level Modelling. This system is not capable of creating spatial simulations, but it can be used as an example for spatial vegetation models, such as the model of Millington et al. (2009). In Rule-Based Community-Level Modelling, vegetation succession is modelled by applying rules based on theoretical knowledge. This makes it useful in study areas where quantitative data is not sufficient.

Vegetation in Rule-Based Community-Level Modelling has similarities to state-and-transition modelling and has four variables: the state, the duration it has been in that specific state, the direction of the change depending on environmental conditions and the time required to transform into that state. Environmental conditions can change during a transformation, which in turn can alter the direction and time required of vegetation succession (McIntosh et al., 2003).

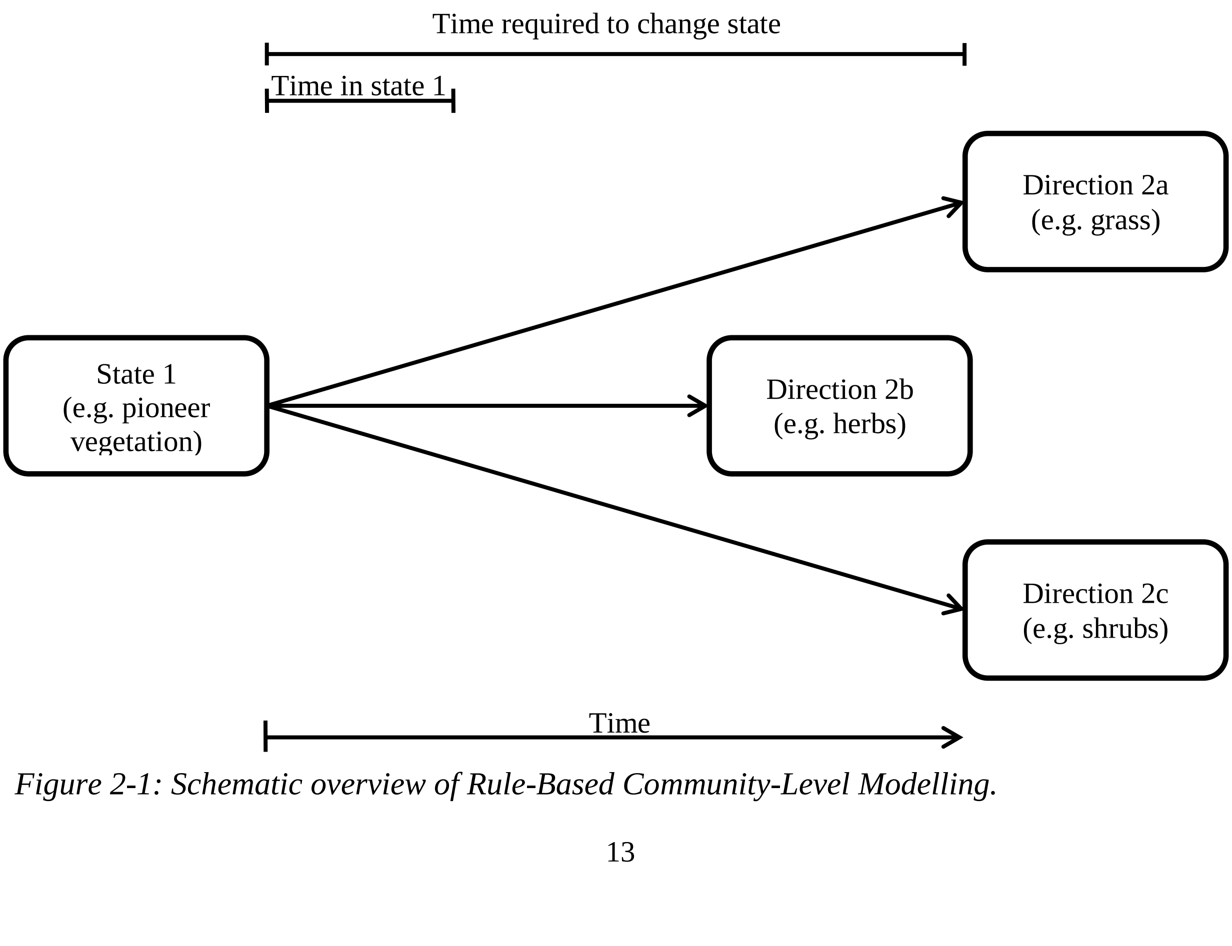

Figure 2-1: Schematic overview of Rule-Based Community-Level Modelling.

The model of Millington et al. (2009) consists of multiple smaller calculations. Depending on the type of class and the duration that a pixel has been in one class, a calculation is made to decide if a transition occurs and how much time that particular transition takes. This calculation depends on seed dispersal, soil moisture and solar radiation. Seed dispersals determines how far a plant type can spread from the original location, as seeds only travel within a limited range. Soil moisture is used to determine what areas are dry and what areas are moist, which affects the spread of different plant types. Solar radiation affects where specific plant types grow better. Vegetation that requires sunlight is more likely to grow on the southern sunny side of slopes. Vegetation that is tolerant to shade, will grow on the locations with more shadow.

2.2.3. Agent-based flood models

Most of the agent-based models related to floods do not model the occurrence and progression of floods. Instead the models simulate the impact of floods. For example, Saadi et al. (2017) use static flood maps as input for an agent-based model on the impact of the flooding of the Meuse on Belgian travel demand. Another example is from Tagg et al. (2016), who describe some new developments of the Life Safety Model (LSM), which is an agent-based model. This model predicts the damage that floods can inflict on people, vehicles and buildings. However, this model also does not model floods and relies on the output of 2D hydraulic models.

Benninga (2013) also used a flood model to predict flood risk perception. This model is relatively simple in comparison to other flood models. The advantage of this model is that it only requires very little input and the results are easy to understand for non-experts. The water level is compared to the local elevation. Areas with a lower elevation than the water level are flooded.

Dawson et al. (2011) are an exception and have included a flood model in an agent-based model for risk-based flood incident management. While this flood model does not contain agents itself, it is an example of how a flood model can be created within an agent-based model.

The inundation model has the following variables: the water surface height, cell dimensions, the volume of the water and the roughness of the surface. Flow depth is also used in this model, which is the difference between the highest water surface and the highest riverbed of the two cells (Dawson et al., 2011).

Inundation in this model is simulated by two equations. The first equation calculates the difference in water surface height for two raster cells. The difference in water surface height is used in combination with the friction coefficient and the flow depth in the second equation to determine water flows (Dawson et al., 2011).

2.2.4. Other flood models

An example of a non-agent-based model is the model of Berger (1991), who has created a model to forecast floods of the Meuse 24 hours ahead of time. Since the Meuse flows through three countries, the data availability varies per nation. To solve the problem of varying data availability and varying river characteristics, the model has been split up into three parts along the country borders.

The Dutch part of the Meuse is the most similar to other rivers in the Netherlands due to its location downstream and the smaller slopes. Because the floodplains have different attributes than the river channel, water flow predictions of the two parts are made separately. In the model floods depend on two factors: the water flow velocity and the discharge (Berger, 1991). The flows in the river channels are predicted with river channel profile data, while the flows in the floodplains are modelled with maps on inundation, flow velocity dependent on the discharge and topography and information on the relation between water height and the discharge (Berger, 1991).

The discharge is calculated by adding the predicted change in discharge to the measured discharge. The predicted change in discharge is in turn dependent on the amount of precipitation and snowmelt. Thiessen polygons are used to determine whether or not the precipitation flows into the river, while snowmelt adds a constant amount of discharge each time step (Berger, 1991).

Yamazaki et al. (2011) created a model that is specifically focussed on floodplain inundation, named CaMa-Flood. Because previous models used a coarse spatial resolution, the smaller topographic features were not taken into account, resulting in an inaccurate representation of floodplain inundation.

This model uses the results of a land surface model and a river network to calculate routes for the runoff to the coast on a grid. The model calculates for each grid point the water storage of the rivers and floodplains, river discharge and the depth and level of inundation. The total water storage consists of the storage of the river channel and the floodplains. When the total water storage is known, the other variables can be determined. When the total water storage is less than or equal to the capacity of the river, the floodplains are not inundated. If the total amount of water stored is higher, the water storage in the river channel can be calculated by deducting the water storage of the floodplains from the total water storage. This information can be used to determine the water depth in the river, the water depth in the floodplains and the area of inundation (Yamazaki et al., 2011).

The water storage itself is calculated by using data on the current water storage, the discharge, the upstream discharge, the catchment area and the runoff calculated by the land surface model. The discharge is determined by using a simplified version of the Saint-Venant equations, which is a common method to calculate water flows. The discharge is also equal to the flow velocity multiplied with the height and width of the river. Flow velocity in turn is dependent on the roughness and the river depth (Yamazaki et al., 2011).

These are only two examples of flood models. There are many more existing flood models that could be integrated in the vegetation model. However, covering all the existing models is beyond the scope of this research.

3. Model design

3.1. Conceptual model

To create an overview, a conceptual model has been made for the vegetation development, as displayed in figure 3-1. This conceptual model is divided into three sub-models, similar to figure 3-1.

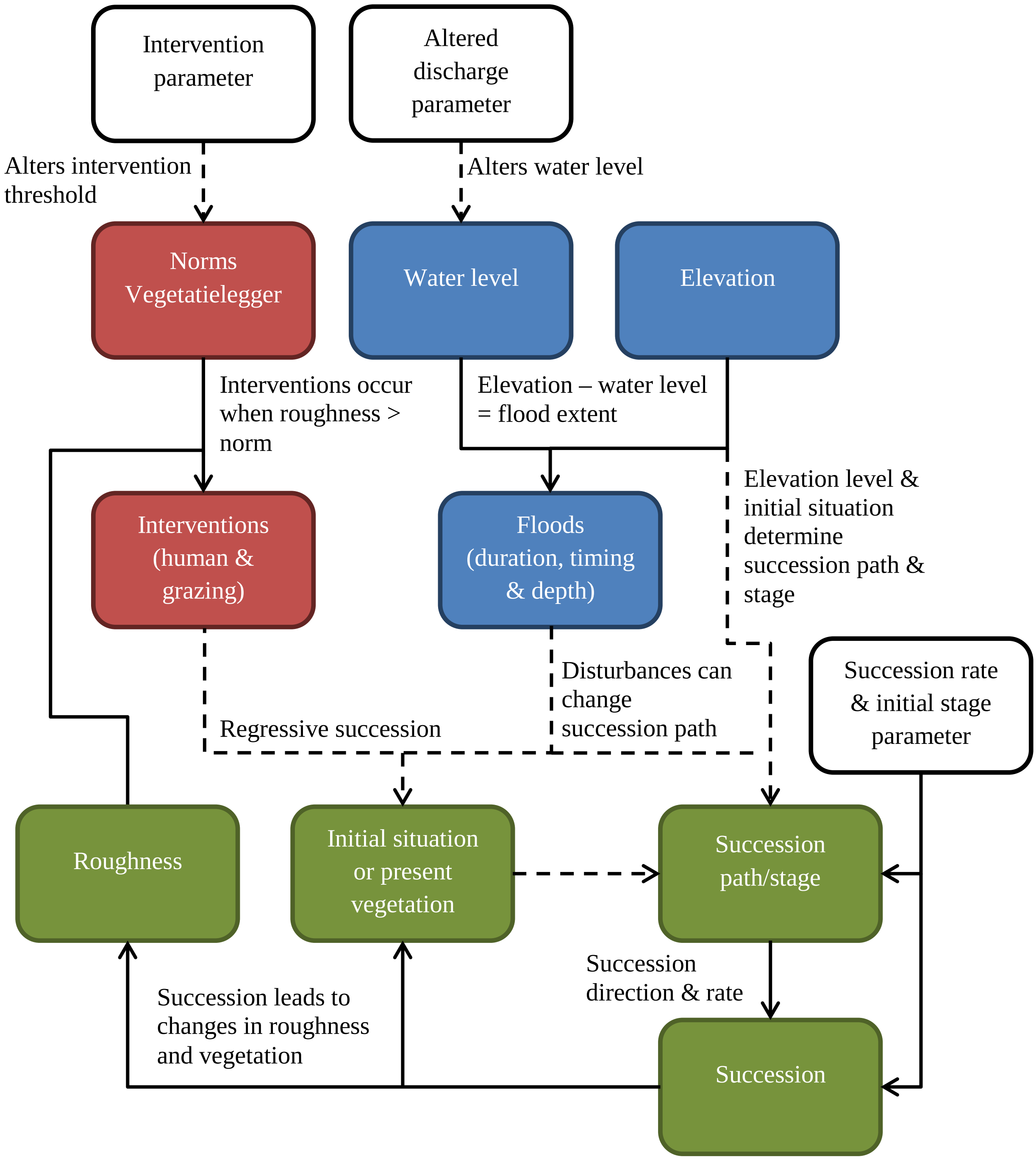

Figure 3-1: Conceptual model of vegetation development. Green is the vegetation model, red the intervention model, blue the flood model and white are user inputs. The dashed arrows represent discontinuous relations.

Succession determines the roughness of a floodplain, which in turn influences both human interventions and floods, as was explained in figure 1-3. By using an existing flood model, the effect of roughness on floods cannot be integrated in the model. Therefore, this relation is not shown in figure 3-1.

Human interventions and floods are, together with grazing animals, disturbances that change present vegetation. The norms of the Vegetatielegger together with the roughness determine the interventions, while grazing is not affected by any factors within the conceptual model. The intervention parameter determines how many cells are allowed to exceed the norm, before interventions will occur. The extent of floods (flood duration, timing and depth) is determined by comparing the elevation level with the water level. The water level can be altered by the water level parameter. Interventions and floods cause regressive succession, while grazing halts the succession process. The dashed lines between the disturbances and succession represent the fact that disturbances do not continuously occur. Similarly, the parameters only influence the model if they are changed by the user.

Succession itself is determined by the path and stage an area is in within the succession matrix or succession schemes. Both the succession rate and direction can be derived from these succession stages. In turn, the succession path and stage are dependent on other factors. As the model contains parameters for both the succession rate and the initial stages, the user can influence the succession stage as well. Since there is no standard value for these parameters, the user always influences this part of the model.

At the start of the model, the initial vegetation and the elevation level determine the succession stage. This continues until a disturbance occurs, which can change the succession stage. After a disturbance, the new succession stage is again determined by the water level and the present vegetation. Again, the dashed lines represent the fact that these relations only play a role when disturbances occur.

3.2. Choosing a flood model

As was mentioned in the introduction, vegetation development will be modelled with an agent-based model. To keep the model simple, an existing flood model will be used as input for the vegetation model. A downside of the external flood model is that changes in the roughness due to vegetation development do not affect the floods. In figure 1-2 (chapter 1) this means that the arrow going out from the vegetation model to the flood model is not included in this research.

There are some requirements for the flood model. First, the output of the model has to be usable in the agent-based model. Secondly, the model must accurately represent the floods in the research areas. Finally, the model should be able to model both the current water level as well as altered water levels.

A range of flood models has been discussed in sections 2.23 and 2.2.4. However, most of these models are difficult to integrate in a vegetation model. The primary reason for this is that the majority of these models require a lot of data, such as data on precipitation and water flow velocity. This is particularly difficult due to the fact that the vegetation model will be used to simulate the future, for which precipitation and discharge for example remain largely unknown. Furthermore, properly integrating a complicated flood model would require a lot more knowledge on river hydraulics and flooding, which would go beyond the scope of this research. Finally, most flood models are not agent-based and would need to be converted. To convert such complex models would require a lot of work and could be considered a research project on its own.

Therefore, the relatively simplistic flood model used by Benninga (2013) was chosen. This model requires only water levels for each time step as input and is already integrated in an agent-based model. Since this input has the format of a list, any time step can be used in this model. This makes it easier to integrate in other agent-based models, such as the one for this research. Furthermore, the effects of an altered water level can be easily included in this flood model.

As shown in figure 3-1, the chosen flood model compares the average water level of the month with the elevation of each cell to determine the flooded areas. Areas with a lower elevation than the water level are flooded in the model.

3.3. Vegetation model

In this model, vegetation will be simulated cell by cell. Each cell contains a value for each vegetation type in the model, which corresponds to a certain ecotope. These values represent the percentage of the cell that is covered by that particular vegetation type. Zero percent (0%) in any of the vegetation types signifies that that vegetation type is not present in the cell. Figure 3-2 shows an example of the vegetation composition of a raster cell.

Over time the percentages of vegetation change due to succession. As was explained in the previous sections, this change has two components: a succession direction and a succession rate. Both of these are determined by the succession stage that is assigned to the cell, which in turn in dependent on the elevation level and present vegetation types. The modelling of succession will be covered in the next section (3.4). Changes in the vegetation percentages can also be caused by human interventions, grazing and floods. These will be covered in section 3.5, 3.6 and 3.7 respectively.

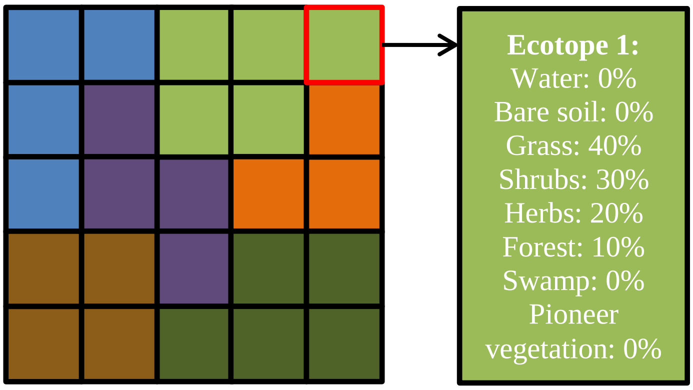

Figure 3-2: Example of the composition of a raster cell.

3.4. Succession matrix & succession schemes

The simulation of ecological succession will be the core of this model, as it is one of the major factors in vegetation development. Peters (2002) has created a succession matrix of the floodplains in the Netherlands. This matrix depicts the development of vegetation on different heights with varying starting land uses. The succession matrix will be used as guide for modelling ecological succession.

In the succession matrix, an ecotope results into another ecotope over a certain period of time. As was stated in the literature overview, ecotopes are not ideal for modelling succession. However, the succession matrix also contains percentages of plant species at different intervals for each succession path. These are more suitable to model gradual changes with. In the model, these percentages will slowly change from the starting ectope to the percentages of the succeeding ecotope.

The heights in the matrix are not based on the actual elevation but on the frequency of inundation. For the vegetation model these frequencies are dependent on the output of flood model.

As was described in the literature overview, the matrix does not include the disturbance factors in the floodplains. Floods and interventions do not necessarily lead to the same results. The exact effects of these disturbances will have to be determined in another way and will be elaborated in the next sections.

However, the succession matrix has some limitations. For the matrix it is assumed that every initial situation is a result of human actions. While this could be true for the Dutch floodplains, most initial situations are not recognisable anymore in the Duursche Waarden. For this reason the user can set the vegetation composition of the starting situations that are defined in the succession matrix. The matrix also only contains specific vegetation compositions for each succession stage. Therefore it is not possible to assign every cell to one of these succession stages.

To model succession for the remaining cells that cannot be assigned to any succession stage, the succession schemes of Van Velzen et al. (2003) are used. This is a more general method of modelling succession, as it is less dependent on location. Only the elevation and floods matter for this method, because these schemes only make a distinction between low and high areas.

The downside of the succession schemes is that these do not contain any information on the succession rate. To solve this problem, the user can set the succession rate of each vegetation type.

Figure 3-3 shows how succession is handled with the two different methods. In the first step, a decision has to be made on the method of simulating succession. After that, succession progresses in accordance with the chosen method. This approach is similar to state-and-transition models mentioned by Spies et al. (2017). Each cell has a stage assigned (state), which determines its succession direction and rate (transition).

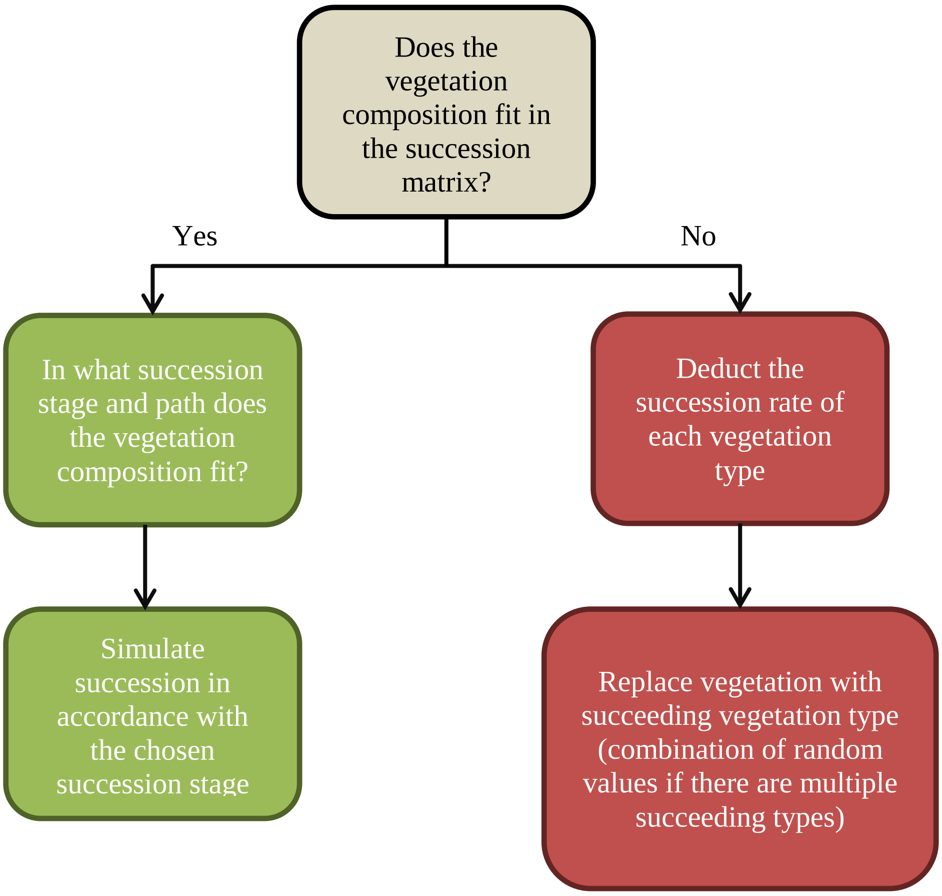

Figure 3-3: Flowchart of succession in the model.

3.5. Human interventions

One of the disturbance factors is human interventions. Because the Duursche Waarden are designated as a natural landscape, the human disturbances are limited. Therefore, the only intervention that will be included in this model is the removal of vegetation by Rijkswaterstaat.

In the literature overview, it was already discussed that Rijkswaterstaat has set norms for vegetation. Rijkswaterstaat has also created an overview of the floodplains for which these norms apply, called Vegetatielegger. This is a map with the currently allowed vegetation in the floodplains. For some areas, vegetation is allowed to change within a certain range. For example, a minimum was set for grasslands and agricultural fields and a maximum for the forests. The Vegetatielegger also has some additional rules (Rijkswaterstaat, 2014):

- Isolated trees are allowed to grow in the floodplains.
- Existing hedges are allowed to form lines.
- In areas where the norm is a homogeneous class, the growth of vegetation with a higher roughness is allowed as long as it does not cover a continuous area that is larger than 500m².

However, these additional rules are not implemented in the model for various reasons. The first two cannot be implemented, because the model simulates vegetation development as percentages of each cell. Implementation of isolated trees and hedges would require the model to simulate individual trees and shrubs. The last rule is implemented in a slightly different way with a parameter. Without this threshold , the Rijkswaterstaat agent would intervene as soon as a tiny area (single cell) exceeds the norm. This is not very realistic, as it would be expensive for Rijkswaterstaat to intervene that often. Therefore, a parameter is used to set a minimum area size that needs to exceed the norm before Rijkswaterstaat intervenes. Whenever enough vegetation exceeds the limitations, it will be removed. Rijkswaterstaat and other land owners can be modelled as actors, similar to the agent-based model of Spies et al. (2017).

There are also some assumptions made to model the interventions. The first assumption is that the rules and norms are not changed over time, as this is not predictable. Secondly, it is assumed that when a certain vegetation type in an area has to be removed, it is removed completely from that area. This means that if a forest has to be cut down in an area, that area will have no forest directly after the intervention. This minimizes the amount of required interventions, as it would take a longer time for the forests to regrow and exceed the same limit again. A downside of this assumption is that protected areas and species are not taken into account, which is done by Rijkswaterstaat when intervening. In order to simulate Rijkswaterstaats' attention for these protected areas and to prevent interventions from becoming too devastating, vegetation removal leads to grass instead of bare soil.

3.6. Grazing

In a model, animals could be modelled as agents moving over the Duursche Waarden. Grazing could be simulated by halting succession when a certain amount of grazing animals are present in a certain area. However, this is not required for this particular model as natural grazing is already included in the succession matrix. Highly intensive grazing could lead to a different outcome, but is unlikely to occur, as the research area is a natural landscape.

3.7. Impact of floods

As was explained in the literature overview there are four major factors that determine the impact of floods: vegetation type, flood timing, flood duration, and flood depth.

In the model, floods have varying effects on different vegetation types. Some plants, such as trees and shrubs are more resistant to flooding. Furthermore, vegetation in lower areas and closer to the river will have a higher flood tolerance, because flood intolerant plants are less likely to grow in those areas.

The effect of flood timing is implemented by changing the effect of a flood depending on the month. During the growing season, floods will have a larger impact than during the rest of the year.

Longer lasting floods can have stronger effects than floods with a short duration if they occur during the growing season. However, since the time step of the model is one month, the impact of flood duration is not implemented. The reason for this is that a month already is a relatively long time. It is highly unlikely that any plant can survive submergence for a month during the growing season.

The impact of flood depth is linked to the vegetation group. Foliage of small vegetation types, such as grass or herbs, are already submerged if the water level is higher than the elevation. It takes a higher water level to submerge shrubs, while trees or forests require a very high water level. These differences are included in the model.

4. Data preparation

In previous chapters it was mentioned that multiple datasets are required to run the model. Before adding these datasets to the model, some adjustments need to be made to the data. This will be described in this chapter. Appendix A contains the details of the sources of all the datasets that are integrated in the model or are used for validation.

4.1. Vegetation data

The vegetation data used in the model is derived from research on the Duursche Waarden conducted in 1996 by Rijkswaterstaat which resulted in a map of ecotopes (Rijkwaterstaat, 1996). This map distinguishes more vegetation types than necessary for the model. To reduce the number of groups, the map has been reclassified based on the descriptions and legend matrix that were created for this map by Koppejan (1998).

Prior to the reclassification a number of changes were made to the input data, including:

- Aquatic vegetation was grouped with water.
- The forest class was subdivided.
- In this subdivision vegetation types white willows with creeping bentgrass (b1.96), basket willow and almond willow (b.2.96), common hawthorn (b13.96) and goat willow and blackthorn (b14.96) were classified as young forest or shrubs.
- The remaining forest vegetation types were grouped together as forest.

The first change is that aquatic vegetation was grouped with water, because the model only simulates the development of vegetation on land. Therefore the aquatic vegetation was not relevant for the simulation.

Another change was made to the forest vegetation groups. In the succession matrix a distinction is made between old forest on the one hand and young forest and shrubs on the other hand. The map does include a distinction between tall and small forests, but this distinction has no values attached. Therefore the percentage of old and young forests could not be determined using this distinction and the forest had to be divided in different groups.

Most vegetation types were assigned to either a young or old forest class by examining the groups used in the map data. These types only appeared in either the small or tall forests class, respectively. Using this method, vegetation types b1.96 and b2.96 in the map data were classified as young forest, while the vegetation types b4.96 up to and including b12.96 in the map data were assigned to the old forest class.

Vegetation types white willow (b3.96), common hawthorn (b13.96) and goat willow and blackthorn (b14.96) could not be assigned to a class using the previous method as they appeared in both the small and tall forest classes of the map data. The classification of these remaining three classes is not in correspondence with the classification at the end of the document of Koppejan (1998). The reason to deviate from this classification is that it is important to group vegetation types with similar roughness together. This would ensure correspondence between the interventions in the model would resemble and the actual interventions.

The white willow vegetation class (b3.96) was classified as old forest, because the description states that it has a height between 5 and 20 meters, which is taller than the vegetation types that are already classified as young forest. Due to its length it would not have a roughness value comparable to shrub vegetation but is more similar to the old forest vegetation group. Furthermore, all the areas that have more than 50% of this vegetation type are considered to be old forest, according to the legend matrix in the documentation of the data.

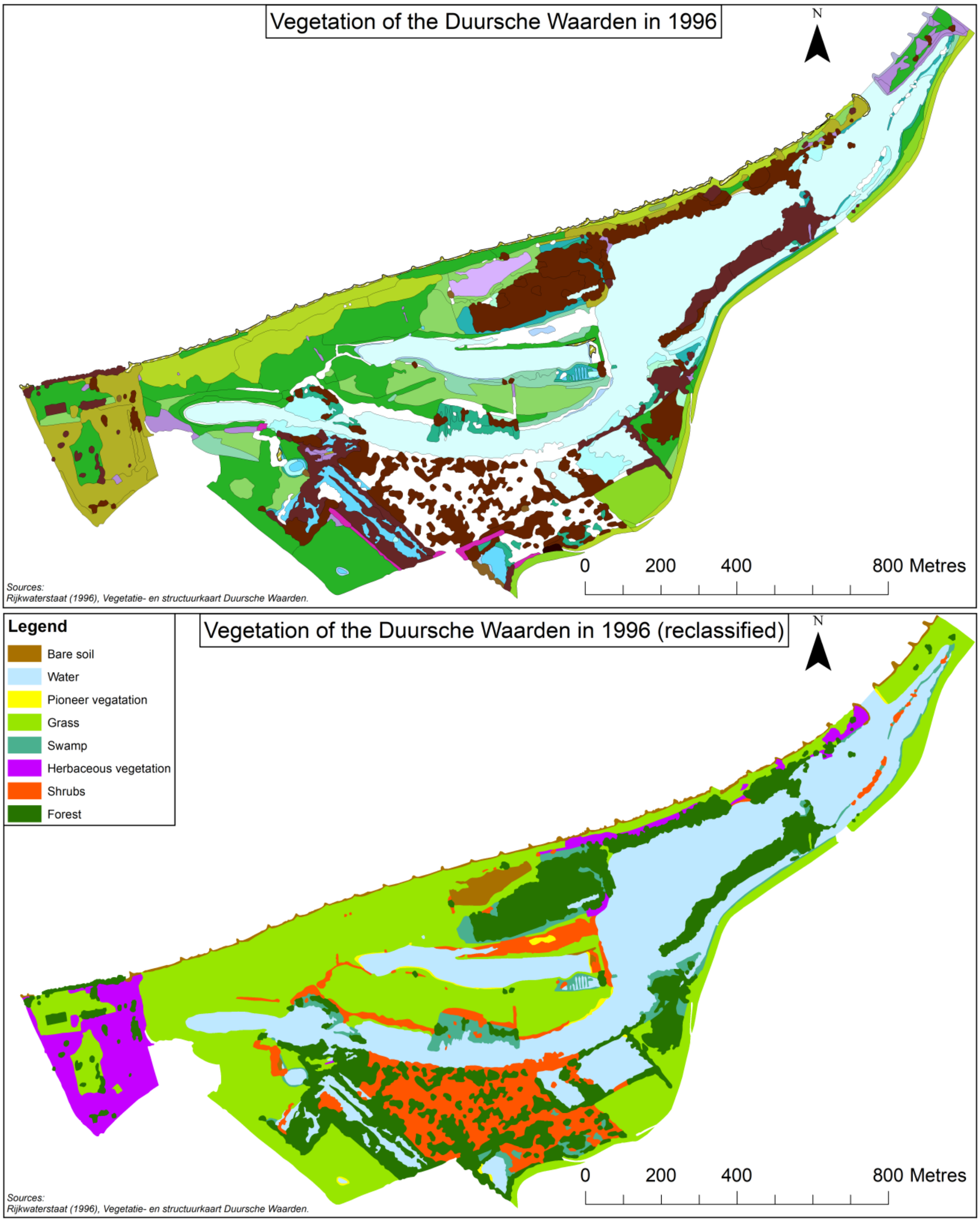

Figure 4-1: Comparison of the original and classified map.

Vegetation classes common hawthorn (b13.96) and goat willow and blackthorn (b14.96) were classified as young forest using the same method. These classes have a shorter height and when their presence in an area is larger than 50%, they are always assigned to the small forest class in the matrix legend. In addition, these vegetation types have branches near the ground, which would increase the roughness.

The reclassification resulted in six vegetation classes and two classes that represent lack of vegetation:

- Pioneer vegetation
- Grass
- Swamp
- Herbs
- Shrubs or young forest
- (Old) forest
- Bare soil
- Water

In figure 4-1, the original vegetation map is compared to the reclassified vegetation map. No changes in visualisation were made to the original map to reflect the large number of classes in the data. Due to this large number of classes, the legend is separated from the map and can be found in appendix B. The classes in the original map are ecotopes, while they represent the largest vegetation group of each area in the reclassified map. Some areas in the original map have vegetation percentages, but do not have a class, which causes the white areas on the map. After the reclassification of the vegetation, raster files were created for each class to make the data usable in the agent-based model.

4.2. Water data

Data on the water level between 1996 and 2017 was gathered from waterinfo.rws.nl. The data on this website is maintained by Rijkswaterstaat and contains the water level for each hour of the day at various measuring points along the Dutch rivers. Only the data of the measuring point near Wijhe was used, as it is the closest point to the Duursche Waarden (see figure 4-2). This measuring point is located downstream of the research area and the data could therefore be slightly inaccurate for the Duursche Waarden.

Only the water level at 08:00 of each day was used, because that is the only time with data before 2006. This also limits the amount of data necessary. Using those water levels, the average of each month was calculated. Smaller time steps, such as days or hours, were possible, but not practical due the fact that succession progresses slower. A downside of months as time steps is that the average can be inaccurate when the data has outlier values. This inaccuracy would increase with even larger time steps, such as years.

The water level data is stored in a separate text file in which each entry is the average water level of one month. The order of the entries determines the order of the floods. When the last entry (12-2017) in the dataset has been reached, the model will start from the beginning of the dataset again (01-1996).

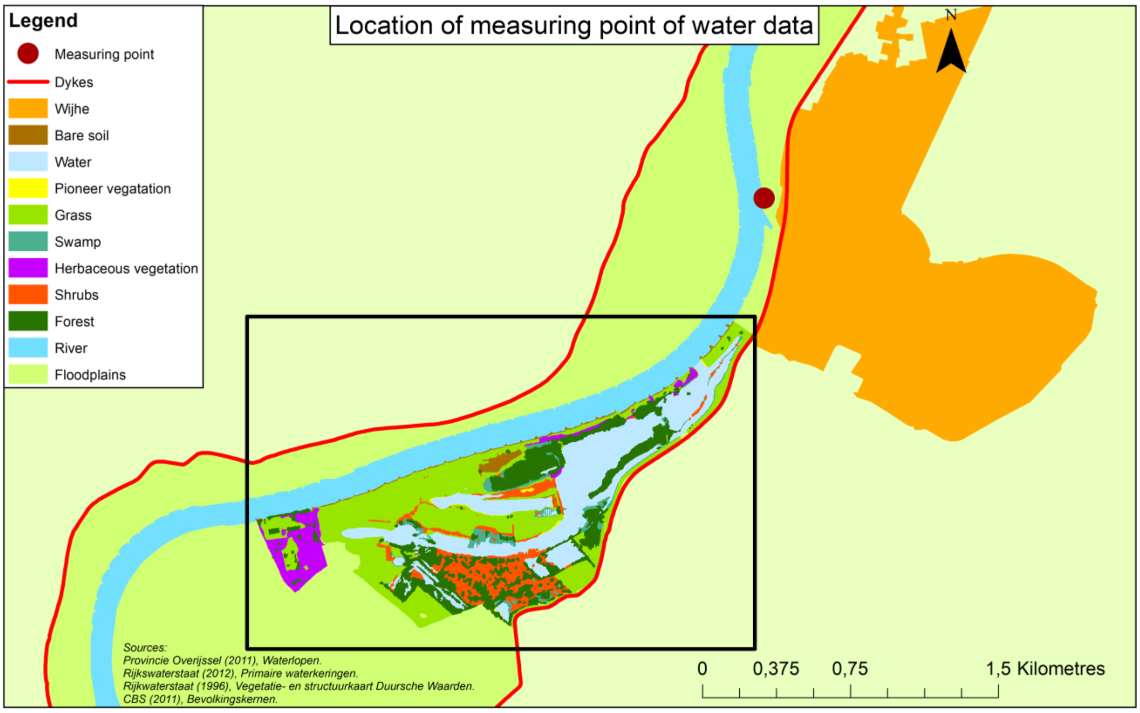

Figure 4-2: Location of the water data measuring point.

4.3. Elevation data

The elevation data was acquired from AHN2 (Algemeen Hoogtebestand Nederland). This is a raster map of the height of the entire Netherlands for different spatial resolutions divided in smaller rectangular pieces of 6.25 km by 5 km. Due to this division the elevation data of the Duursche Waarden is spread over four of those pieces. These pieces were first merged together before the data outside the research area and its surroundings where removed. It was also assumed that all ‘no data’ cells had a height equal to the NAP level, because there was no data for elevation under water.

Using this elevation dataset and the water data, three elevation levels were created in accordance with the succession matrix of Peters (2002). These elevation levels are dynamically created each time the model is set up, because of the role the levels play in succession. These elevation levels are not based on the actual height, but on the flood duration per year:

- High (In matrix 0 – 20 days inundated per year): Every cell that is inundated 30 days per year or less.
- Middle (In matrix 20 – 100 days): Every cell that is inundated between 30 and 90 days.
- Low (In matrix 100 – 365 days): Every cell that is inundated more than 90 days per year.

For simplicity’s sake, this calculation is only done with the water levels of the first year and it is assumed that in later years these elevation levels remain roughly the same. A different method could be used to define a flood by for example basing the elevation levels on all the years. However, this is difficult to execute in the current version of the model. The elevation levels are dynamically determined by the model, based on the water level data, to make it relatively easy for the user to use their own data and research area. To achieve this, the water data is in the form of a list, without any means to distinguish each year. This list is sorted from large to small numbers to determine the elevation levels. Without a way to distinguish the input years from each other, sorting the water data of multiple years would mix the years together. As a result, it is not possible to determine how often a certain height was flooded in a year, which is used to determine the elevation levels. Sub-lists for each year of water data would be a possible solution for this. However, one user may have a larger water dataset than another user, which makes the creation of these sub-lists complicated as well.

Another assumption was that every month is 30 days, because the time steps in the model are measured in months. The numbers of the succession matrix are also adjusted to full months, allowing the model to calculate the elevation levels of the cells. By calculating the elevation levels in the model, the water and elevation datasets can be exchanged without the need to alter other datasets or the model itself.

One exception to these classes had to be made. Because the succession scheme of Van Velzen et al. (2003) does not include a succession direction for swamp vegetation in the high elevation class, any cell with swamp vegetation is set as low elevation.

4.4. Other datasets

The data on the norms of vegetation is gathered from the Vegetatielegger of Rijkswaterstaat. There are eight possible classes in this dataset, each with different limits. Table 4.1 displays how the classes are translated into the model. The classes row in the table is used to make distinction between the different norms in the model. The numbers in that row only have a meaning within the model.
The final dataset used was on the areas protected by dykes. The zones used in the model are derived from data of Rijkswaterstaat on dyke rings, included in the dataset 'Primaire Waterkeringen' (Rijkswaterstaat, 2012). Only the shape of the dykes within the research area were included in the model.

After all the preparations, the datasets used in the model were converted to ASCII format. These conversions were necessary for importing the geographical data into Netlogo, which is the program used to develop this model.

Vegetatielegger	Intervention at	Class in model
Grassland and fields	Grass, bare soil, pioneer & water < 100	1
Reeds and herbs	Swamp, herbs, grass, bare soil, pioneer & water < 100	2
Forest	Swamp, herbs, grass, bare soil, pioneer, forest & water < 100	3
90/10	Grass, bare soil, pioneer & water < 80	4
70/30	Grass, bare soil, pioneer & water < 30, shrubs + forest > 40	5
50/50	Grass, bare soil, pioneer & water < 10, shrubs + forest > 60	6
Shrubs	No interventions	7
Paved terrain and water	Intervention with any vegetation type, theoretically no vegetation growth either	8

Table 4-1: The implementation of the classes in the vegetation model.

5. Model implementation

Model implementations are often described in accordance with the ODD protocol. This protocol is a standardized method used to communicate information on agent-based models (Grimm et al. 2010). The structure of the description of the model implementation has some similarities to the ODD protocol.

5.1. Purpose

The goal of this model is to predict how vegetation in the river floodplains will develop while taking ecological succession and disturbances, such as floods and human interventions, into consideration. Floods can be based on the natural variation in water levels, which can be altered by modifying the water level in the rivers. By doing this, the model should be able to predict vegetation development when the water level changes due to climate change.

5.2. Sub-models

The model consists of three sub-models: a vegetation model, an intervention model and a flood model. The vegetation model simulates the ecological succession process in the river floodplains as well as the interventions done by Rijkswaterstaat.
The flood model is an altered version of the flood model of Benninga (2013). The result of this model is used as input for the vegetation model. Floods are calculated each month by subtracting the water level from the elevation data. If this subtraction leads to a negative number for a cell, that cell is flooded.

5.3. Vegetation model

The vegetation model has no agents, because vegetation is modelled as a dynamic raster environment. Different vegetation types are stored in different raster layers. In total six different vegetation types are included in the model:

- Pioneer vegetation
- Swamp vegetation
- Grass
- Herbs
- Shrubs or young forest
- (Old) forest

In addition, the model contains separate raster layers for:

- Bare soil
- Water
- Elevation
- Norms on vegetation by Rijkswaterstaat
- Zones that represent the areas that are protected by dykes

Each individual raster cell has a value, representing the percentage of coverage of each class. For example, when a cell in the herbaceous vegetation raster has a value of 20, this means that this cell is for 20% covered with herbaceous vegetation. The combination of all vegetation layers should always add up to 100%. These vegetation layers are dynamic and the values are updated every time step.

The model also contains an elevation environment indicating the altitude of every cell. The altitude values are divided into three classes: low, middle and high. Based on a combination of vegetation types and an elevation level, a ‘state’ is assigned to each raster cell in accordance with the succession matrix of Peters (2002). This state dictates the progression of the vegetation development based on the succession matrix. The states are dynamic as well and change when either the cell reaches the next step of the succession path or when a disturbance takes place in the cell. The numbers that are used for each state have no actual meaning, but are used to distinguish between the different stages of vegetation development.

It is assumed that vegetation develops linearly, resulting in the same change in percentages each month. For example, if the percentage of grass grows with 12% in 10 years, the growth per month would be 0.1%. This changes when the vegetation composition has changed in such a way, that it has reached the next stage of the succession path. When this happens, succession rate and direction change in accordance with the next succeeding stage.

The user has to give input to define the initial stage of the succession matrix. For each initial stage, the user is asked the vegetation composition of that stage in percentages. This is necessary as these values are not included in the succession matrix.

Some cells could not be assigned to a state following the succession matrix, because not all possible compositions are covered in that matrix. These cells are grouped in a separate state. Succession in these cells is based on the succession scheme of Van Velzen et al. (2003). The succession scheme varies for low and high areas. The elevation level classes of the other succession method are used for this as well. The middle elevation class is grouped with the high elevation class, because no swamp is present in the classes in the succession matrix of Peters (2002) and the high elevation succession scheme of Van Velzen et al. (2003) does not contain a succession direction for swamp vegetation either.

While the direction of succession can be determined using the succession scheme, the rate of succession is unknown, as this is not included. Therefore, the user can specify the succession rate, by adjusting the sliders that define the decay rate. Each slider determines the percentage that is deducted each month from one of the vegetation types. This number is then replaced by random values of other vegetation types in accordance with the succession scheme of Van Velzen et al. (2003).

5.4. Intervention model

Interventions are modelled by the behaviour of an agent. This is the Rijkswaterstaat intervention agent. This agent is not present in the research area itself, but is able to intervene when necessary. The behaviour of the agent is entirely dependent on environmental variables and user input.

Figure 5-1 shows the behaviour of the Rijkswaterstaat intervention agent. Every year in August the agent monitors the area and counts the number of cells that exceed the vegetation norm. Cells that are expected to be inundated during the next growing season are not counted and are excluded from the intervention. The agent does not take into account whether or not the upcoming flood in a growing season will actually remove vegetation. If the area exceeding the norm is larger than the limit set by the user, Rijkswaterstaat removes the vegetation. This is visualised by placing subagents on all the non-flooded cells requiring an intervention. These subagents are immovable and remain there for a month to make them properly visible. In the month following the placement of these subagents, the vegetation is removed, all succession stages are reset and the count of cells exceeding the limit is set back to 0. The subagents only remove vegetation that can exceed the norm to keep nature intact as much as possible. For example, if no shrubs are allowed in a cell, only the shrubs are removed. However, if there is a limit on forest of 20%, all the forest is removed to reduce the frequency of interventions.

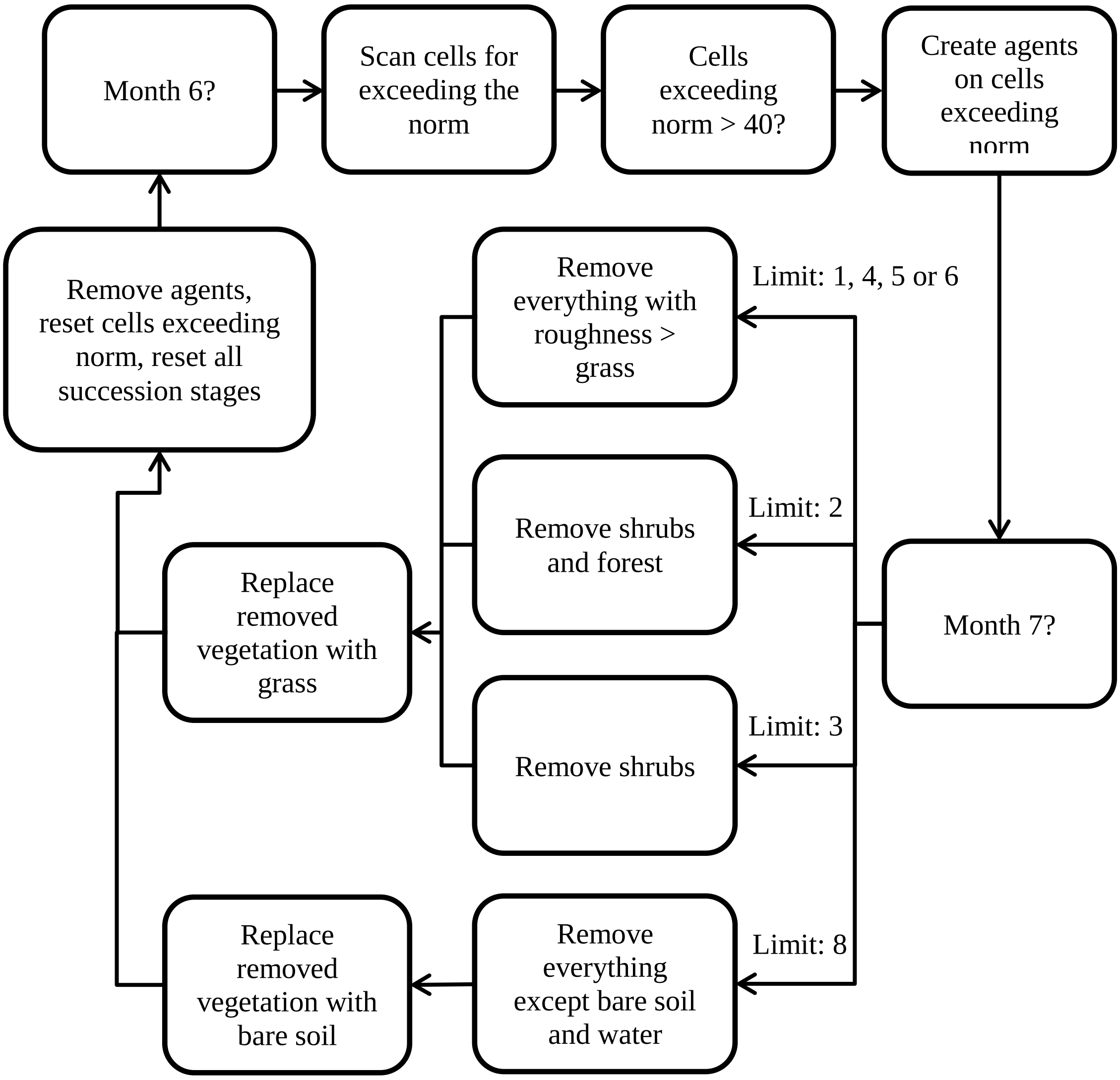

Figure 5-1: Flowchart of the behaviour of the intervention agent. Limits are the same as in table 4-1.

5.5. Flood model

There are no agents that have any effect on the flood sub-model, because the floods are determined by the water level data and the elevation data. The elevation of each cell varies, but the water level is the same for the entire research area. However, the water level can change over time. Each month the next line of the water level file is read and the value in that line is deducted from the elevation of each cell to determine if that cell is flooded.

The water level is also multiplied by the water level parameter. In this parameter the user can increase or decrease the water level by setting the value of this parameter higher or lower than one respectively. However, when this water level is set to such a high amount that it would flood the dykes (700 cm), the model interferes and limits it to the highest possible value.

Flooding is also influenced by an additional environment, called zones. This prevent floods from occurring in areas that are protected by dykes. These zones are based on the dyke ring dataset of Rijkswaterstaat (Rijkswaterstaat, 2012).

The effect of floods varies depending on the time of year, elevation and vegetation type. Floods always halt succession progression as the vegetation types included in the model cannot grow underwater. However, only floods in the growing season (March – May) are able to damage plants.

Vegetation types in the low elevation class are not damaged by floods, representing the flood tolerance of plants that grow in low river floodplain areas. At the high elevation level all plants can be damaged by floods, as these plants are less likely to have developed a tolerance for floods.

The middle elevation level has separate variables to measure the flood tolerance of the vegetation types in each cell. These variables determine how much of the vegetation group is lost during a flood in the growing season. At the start of the model, half of the vegetation in each vegetation group is tolerant to floods. When a flood in the growing season occurs, only the flood intolerant plants are removed. The tolerance of the vegetation types in a cell is updated every time a flood occurs. Half the increase of each vegetation group consists of flood tolerant plants. If a vegetation group decreases to such an extent that the tolerance of that group becomes larger than the vegetation group, the tolerance is set to be equal to the total of that vegetation group.

Not every flood intolerant vegetation type is equally affected by floods in the growing season. Grasses, pioneer and herbaceous vegetation die when flooded during this period. Shrubs die when the flood depth is higher than 1 meter, as flood damage on shrubs and trees increases significantly the more foliage is inundated (Glenz et al., 2006). Forests do not die in the model, because the tree itself does not disappear in a flood. The tree trunk remains increasing the roughness of the floodplains and preventing any other vegetation type to grow in that area. Swamps cannot die in the model. This is not due to the properties of swamp species, but because of the fact that all areas with swamp are classified as low in the model. This was already explained in section 4.3.

Figure 5-2 shows an overview of the flood disturbances. Similar to the interventions of Rijkswaterstaat, all succession stages are reset after a flood removes vegetation. This is necessary to prevent cells with negative values or multiple succession stages.

5.6. Scales

The total area of the Duursche Waarden is 134 hectares. This area is divided in cells with a size of 5 by 5 meters as this was the smallest size of the elevation data that could be included in the model. The other rasterised datasets are set to the same cell size. Because the shape of this area does not fit the model screen perfectly, the surroundings can be seen in the model as well. However, in the areas outside of the research area the vegetation development is not simulated.

The time step of the model is 1 month. There is no predefined end time to the model, but the succession of a cell stops if it reaches the end of the succession matrix. This can take 100-150 years if no disturbances occur. For cells that do not have a vegetation combination that is matched in the succession matrix, the end is reached when the cell is 100% covered by a vegetation group that has a succession rate value of 0. The floods do not have an end, but reoccur in a loop when the end of the water level dataset is reached.

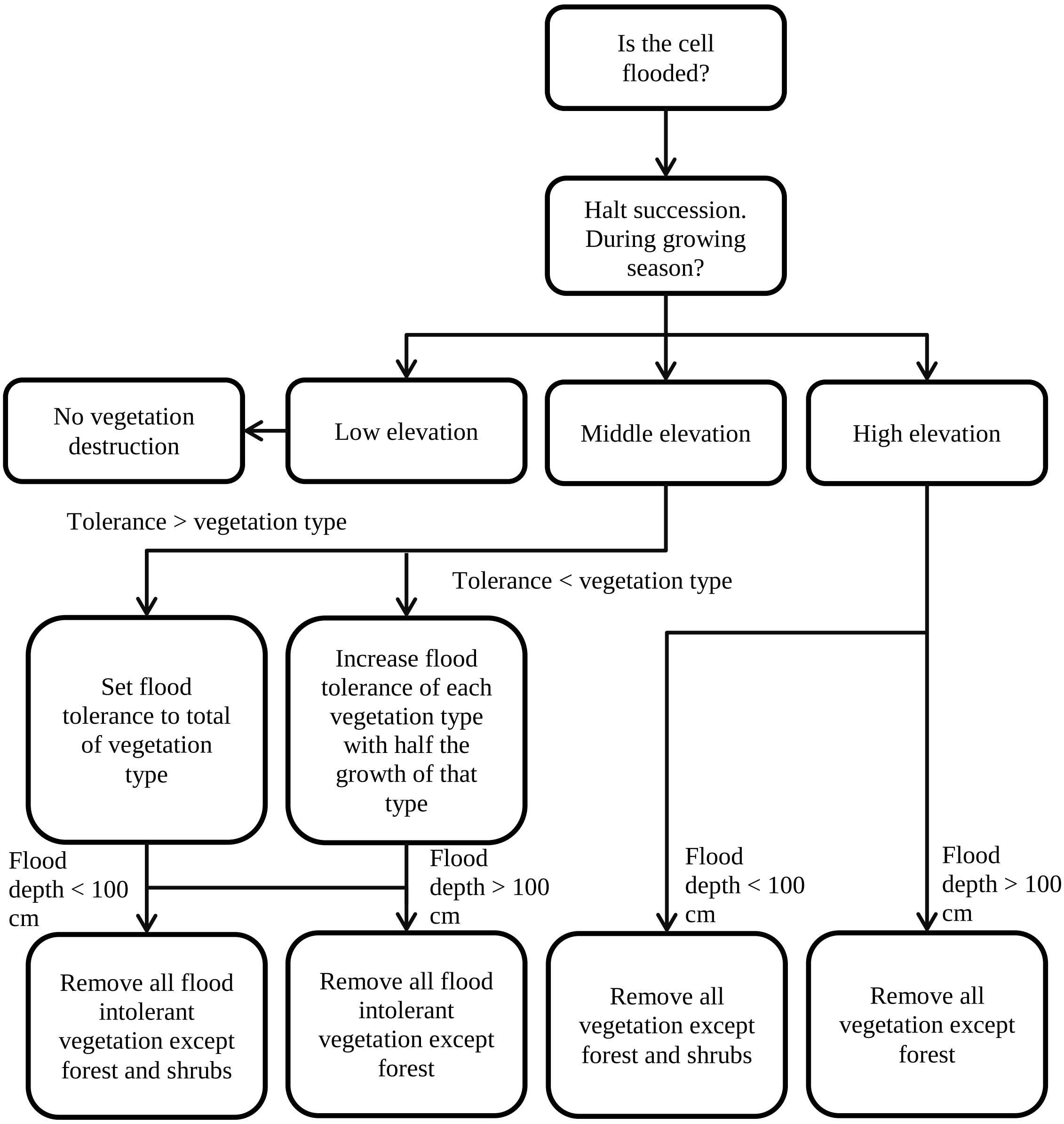

Figure 5-2: Flowchart of flood disturbances.

5.7. Process order

The first step each month is the simulation of the flood in that month. When the current month in the model is between March and May, the damage of the flood on the vegetation is determined after the flood simulation. This is followed by the succession simulation in the cells that are not flooded. Because a cell can only follow one path in the succession matrix, the order in which these paths are simulated does not matter. For each cell the decrease of the vegetation groups is calculated before the vegetation growth, as this determines how much the growth of other vegetation groups.

If the model reaches the month August, the succession processes are followed by the scanning by the Rijkswaterstaat intervention agent, which may lead to interventions. After the scanning by Rijkswaterstaat and a potential intervention, the display of the map is updated with the new data and the model continues with the next time step. Figure 5-3 gives an overview of the process order with references to the figures with more details on each process.

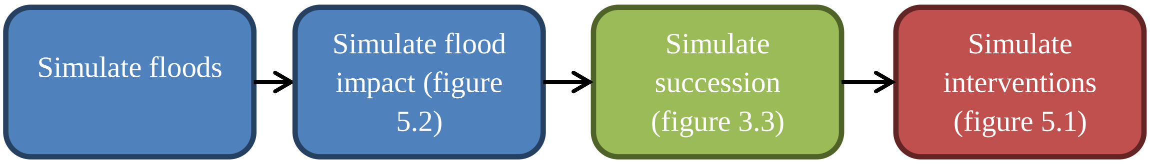

Figure 5-3: Flowchart of the process order in the model.

5.8. Output

5.8.1. General output

For the sensitivity analysis and the scenarios, multiple outputs are created by the model, such as the average roughness and the intervention and flood frequencies resulting from different parameter settings. In addition, every five years the state of the simulated world is exported. This world can then be imported again for further examination, allowing the user to examine the vegetation development over the years. These exports include all of the environments and their variables as well as all the agents. The model cannot restart the simulation from an imported starting situation.

5.8.2. Hydraulic roughness

One output is the calculation of the hydraulic roughness of the vegetation in the research area. The calculation of the roughness allows comparisons to be made between the different vegetation environments. The roughness values can for example be used to perform a sensitivity analysis. The calculations on the roughness are made by using the tables on the roughness coefficient (Manning's n) of Chow (1959) as shown table 5-1.

It is important to note that calculation of the roughness is simplified. Only the average roughness of the vegetation in the research area is calculated. Roughness of the riverbed and the floodplains caused by different sources, such as soil type and slope, are not included, because this data is not included in the model. Therefore the roughness measured in the model is only a small part of the actual roughness of the research area. Before the average roughness of the entire research area is calculated, the average roughness in each cell is determined. This is in turn calculated by adding the roughness of each vegetation type in the cells. The following equation is used to determine the roughness of each vegetation type:

$$R_A = \frac{V_A}{100} C_A$$

In this equation R_C is the roughness of vegetation type A in $s/m^{1/3}$. V_A is the size of vegetation type A in the cell in percentages. C_A is the roughness coefficient corresponding with vegetation type A in $s/m^{1/3}$. This calculation is executed for each vegetation type in the cell. Following these calculations, the roughness of all vegetation types in each cell is averaged, resulting in an average roughness per cell. This average roughness can then be used to calculate the average roughness over the entire research area. The resulting roughness values are comparable to the values in table 5-1. This makes it easier to comprehend if a roughness value is high or low.

Table 5-1 shows the roughness values of the vegetation types. These are based on the table of Chow (1959). This table contains three different roughness coefficients: minimum, normal and maximum. For this research the 'normal' column was chosen. The roughness is only updated once per year in month 6, however the roughness values vary for the summer and winter seasons. A dynamic graph is included in the model, displaying the average roughness of the vegetation in the research area.

Vegetation type	Roughness coefficient
Bare soil / water	0.03
Grass	0.035
Pioneer vegetation	0.03
Herbaceous vegetation	0.05
Swamp	0.05
Shrubs	0.10
Trees	0.15

Table 5-1: The roughness values of the vegetation groups.

Not all these values are directly from Chow (1959), as not all vegetation types that are used in the model are included in Chow. For example, herbs are classified as 'scattered brush with heavy weeds'. Swamp vegetation has the same roughness as herbaceous vegetation, because these are grouped in the same class in the Vegetatielegger of Rijkswaterstaat (2014). Pioneer vegetation has the same value as short grass, while the grass vegetation class itself has the value of high grass. Finally, bare soil and water are grouped together.

The roughness values in the table of Chow for trees and shrubs can also vary due to the size of individual plants. These variations are not included, as plant sizes are not simulated in the model. Instead, the most likely option is chosen with trees and shrubs classified as 'willows, summer, straight' and 'medium to dense brush, in summer' respectively.

There are however some discrepancies between the roughness coefficients given by Chow (1959) and the Vegetatielegger. For example, a major difference is that the former considers trees to be the roughest vegetation group, while the latter classifies shrubs as the roughest vegetation group.

5.8.3. Flood frequency

The frequency of floods is monitored as well and is displayed within a graph. For the purpose of measuring flood frequency, a flood is considered to be a flood when the water level is high enough to inundate any cells at the second elevation level. This elevation level is dynamically calculated in the model, as was explained in the section 5.5.. In the case of the research area of the Duursche Waarden, a flood occurs when the water level is higher than 1.29 meters above NAP.

5.8.4. Intervention frequency

Finally, the model also monitors the frequency of interventions. This intervention frequency is dependent on the vegetation development, floods and the user input. Therefore, this frequency can be highly sensitive to changes. Similar to the roughness and the flood frequency outputs, a dynamic graph of the intervention frequency is included in the model.

6. Results

In this chapter the results of the various tests that have been performed on the model will be discussed. This chapter starts with a robustness test in section 6.1, which is needed for both the sensitivity analysis as well as the scenarios. The robustness test is followed by the sensitivity analysis in section 6.2, which cover the three main parameters: the intervention, water level and succession rate parameters. After the sensitivity analysis, the succession rate is calibrated in section 6.3. In the final section (6.4), the model is tested in varying scenarios. Figure 6-1 shows an overview of the entire chapter.

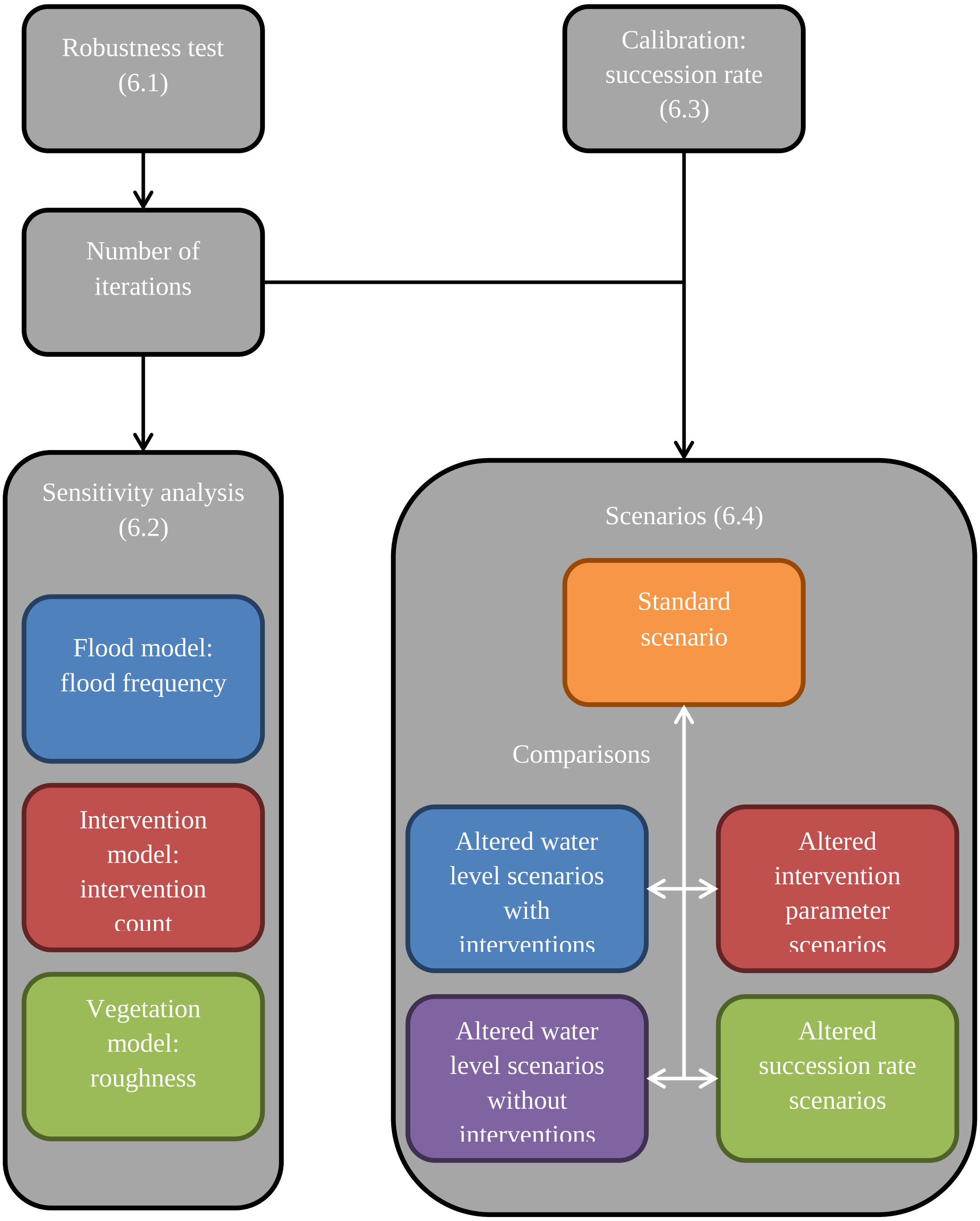

Figure 6-1: Overview of chapter 6.

6.1. Robustness

As was explained in section 5.3, succession is modelled using two methods: the succession matrix of Peters (2002) and the succession schemes of Van Velzen et al. (2003). In the latter method random numbers are used to simulate the rate of succession, as the schemes did not include data on the rate of succession. Because the model contains random elements, using the same parameters could lead to different outcomes. For the sensitivity analysis and the scenarios it is therefore be necessary to run the model multiple times with the same parameters. By testing the model on its robustness, the number of runs needed to create stable results for the sensitivity analysis and the scenarios can be estimated.

The robustness of the model is tested by measuring the average roughness of cells with vegetation at the end of 50 simulated years for a hundred model runs. This average is calculated over all the cells with actual vegetation data in the study area, including the cells that only contain water and do not change over time. The surrounding area only contains elevation data and is not part of the calculations.

All 100 runs use the same parameter settings: the water level and intervention parameters are set to 1 and the succession rate of each vegetation type except forest is set to decrease with 0.08 percent per month. Forest is excluded from succession as it only changes due to disturbances. The parameters for the composition of the starting stages of the succession matrix are excluded by setting the values to zero for two reasons: the research area does not contain some of the succession stages and the starting stages of the matrix have unknown vegetation compositions.

Because some of the succession stages are not present in the research area, applying the parameters for these starting stages would give the wrong results. It is possible that agricultural fields were present at some point in the Duursche Waarden and that these have become unrecognizable due to succession and disturbances. However, the data of Rijkwaterstaat (1996) does not show any sign of recent fields. Therefore, all three agricultural field starting stages do not have any influence on the vegetation development in the floodplains anymore.

Due to the unknown vegetation compositions of the starting stages, it is not possible to use the starting stage parameters. It is, for example, unknown what the size of each vegetation type is in the initial riverbank pioneer situation. Similar to ecotopes, it is difficult to attach values in vegetation cover to these starting stages. Using these parameters would require an expert with more knowledge on succession and the research area.

An exception is the starting composition of the grassland succession paths for all three elevation levels. These are not integrated in the model as a parameter, but it was assumed that grassland consists of 100% grass. It is also still possible for cells that are simulated with the succession scheme of Van Velzen et al. (2003) to end up in any of the succession paths in the succession matrix of Peters (2002). This happens when a cell has a composition equal to one of the known stages in the succession matrix or is between two stages that follow each other up in the matrix. For example, when a succession path has one known stage with the values 70% grass and 30% herbs and the next stage on the same path contains 40% grass and 60% herbs, any cell with 50% grass and 50% herbs would be start developing in accordance with this succession path. If there is a vegetation type present in the cell that is not present in either of the succession stages, the cell will not follow the succession matrix and will use the succession scheme instead.

Figure 6-2 shows the average roughness of the simulated area and the accumulated average of all runs. The graphs for individual vegetation groups show similar results. After approximately 50 runs the accumulated average does not change anymore. Therefore a minimum of 50 runs is needed for the sensitivity analysis and the scenarios.

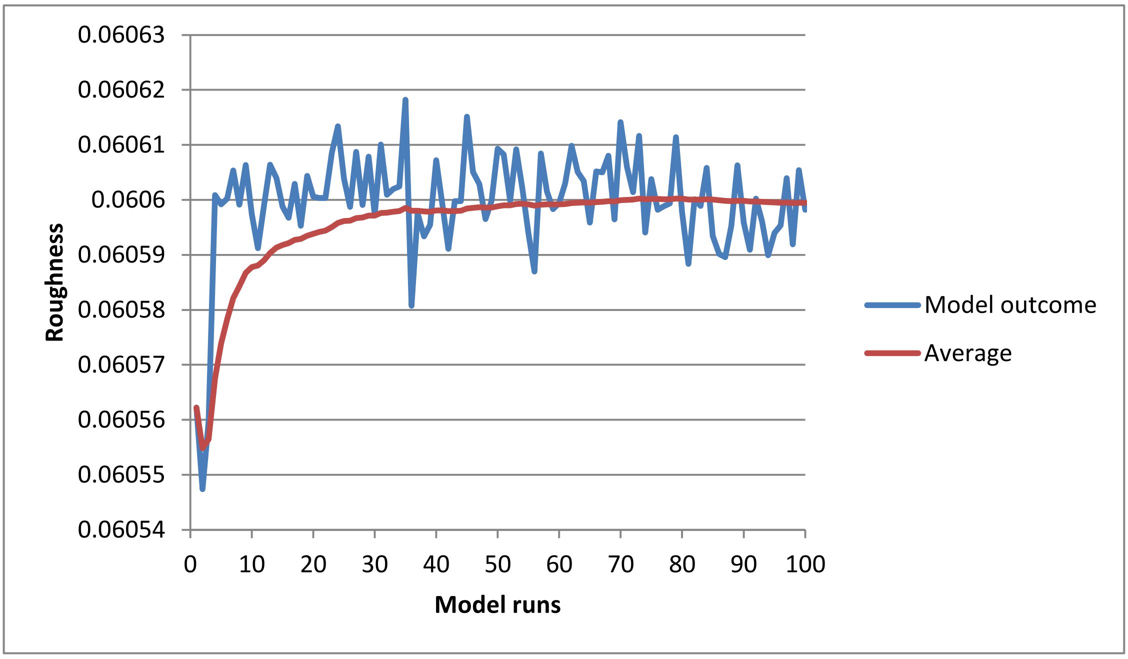

Figure 6-2: The average roughness of each run and the average between runs.

6.2. Sensitivity analysis

In this section the sensitivity of the model to the parameters will be evaluated. To achieve this, separate sensitivity analyses are done for each of the sub-models, using the one-at-a-time sensitivity measurement method. With this method the sensitivity is measured by altering one parameter, while the rest remains the same (Hamby, 1994). When the effect of the succession rate parameter is not tested it has a value of 0.08, similar to the robustness test. Forest again have a succession rate of 0 in this analysis. The water level and intervention parameters are set to 0 and a very large number respectively to prevent any effects on the analysis while these are not tested.

For all parts of the sensitivity analysis, the model will simulate up to fifty years. This is long enough to evaluate the effect of the succession process. Three parameters will be varied to measure the sensitivity: the water level (WL) will be used for both models, the size of the area that needs to exceed the norm before Rijkswaterstaat intervenes (IA) and the succession rate will be only used for the vegetation model.

6.2.1. Flood model

The sensitivity of the flood model is relatively easy to measure as floods are only dependent on two factors: the water level dataset and the water level parameter. Because the water level dataset is static and therefore not dependent on interventions or vegetation types, only the effect of varying water levels has to be measured. This effect can be measured by counting the number of floods. As was stated in section 6.7.3., a month with an average water level of 1.29 meters or higher is counted as a flood.

Table 6-1 shows the flood frequency under different water levels. It was expected for a WL of 1 - no altered water level -, that the flood frequency would be lower than 150 months (3 flood months per year). The reason for this expectation is that the middle elevation level class in the succession matrix of Peters (2002) is inundated 30-100 days per year, which is slightly more than 3 months per year at most. Therefore the flood frequency with no change in the water level is very high. This is caused by the definition of a flood, which is based on the elevation levels. This in turn is derived from the water levels of only the first year (1996), which happens to be a year with a relatively low water level. As was explained in section 4.3, it was problematic to create a better definition of floods.

Water level parameter	Flood frequency (months with water level above 1.29 meters)	Change compared to reference scenario
0.5	54	-87.53%
0.75	241	-44.34%
1	433	0%
1.5	556	28.41%
(1.89 -) 2	575	32.79%

Table 6-1: The flood frequency for different water levels.

For double the WL, the model decreased the water level parameter, because the water level would exceed the height of the surrounding dykes. The parameter was limited to a maximum of 1.89.

6.2.2. Intervention model

Table 6-2 contains the effect of the IA on the total amount of interventions within 50 years with and without floods. The effects of a faster succession or an increased water level were tested as well. However, these two parameters did not have any effect on the total number of interventions when the intervention parameter is set to one hectare. Table 6-2 also shows the result when floods are included in the model to demonstrate that inundation can have an impact on the intervention frequency under different parameters.

The number of simulated interventions is primarily determined by the intervention parameter. Succession rate has no influence on the number of interventions due to the linear vegetation development in the model and the fact that succession generally leads to rougher vegetation types. A cell with 100% grass for example can have a norm that states only grass and other vegetation types with similar or lower roughness values or allowed to grow in that cell. Because of the succession direction, grass in the cell will gradually be replaced by herbaceous vegetation, which has a higher roughness value. Moreover, due to the linearity of vegetation development in the model, the cell will already contain a small percentage of herbaceous vegetation the next month and will therefore exceed the norm. Even if an intervention sets the cell back to only containing grass, the cell would already slightly exceed the norm the next month.

IA	Intervention count (without floods)	Intervention count (with normal floods)
0	50	50
1	50	50
2	50	50
3	50	50
4	50	46.7
5	50	39
6	50	36
7	36.7	36
8	4	13.1
9	3	4
10	2	2

Table 6-2: The average total of interventions under different norm limits.

Succession rate is more significant for the intervention count of cells with a more nuanced norm, where rougher vegetation types are allowed to exist to a limited extend. In a cell where for example 20% shrubs is allowed, the norm would not be exceeded as quickly as in cells where certain vegetation types are not allowed at all. However, this norm type is only applied to a small part of the research area.

Due to this combination of linear succession and different norms in model, there is a certain number of cells that will exceed the norm every year. With a higher IA, the intervention frequency becomes more realistic. When the parameter for the number of cells that are allowed to exceed the norm is increased, the number of required interventions within the 50 simulated years is drastically decreased. To reduce the number of interventions in scenarios with a low IA, succession would have to be non-linear in the model. Additional rules for interventions, could also help to reduce the number of interventions. An example of such a rule could be that cells only require interventions if the vegetation types with exceeding roughness values reach a certain size within that cell. This would be a rule that is not mentioned in the Vegetatielegger itself. However, it is stated by Rijkswaterstaat (2014) that objects smaller than 5 by 5 meters are not included in the norms of the Vegetatielegger. The proposed additional rule could improve the simulation of the interventions by allowing the model to disregard smaller objects as well.

In table 6-2 a situation with floods lowers the need for interventions when the intervention parameter is set between 4 and 7. However, if the parameter is set to eight, the floods lead to a higher number of interventions compared to the model without floods. The reason for this is that interventions cannot be done on cells that are flooded. When an intervention occurs while cells are inundated, the intervention will not remove the same amount of vegetation as without the floods. Furthermore, as was explained in the model description, areas that will be flooded next spring are excluded from interventions as well. Spring floods can thus either reduce or increase the number of interventions, depending on their impact.

6.2.3. Vegetation model

The results of the vegetation model are aggregated in the roughness value (RV), as was explained in the previous chapter. This value is directly derived from the vegetation groups and is therefore dependent on the succession rate parameter. However, roughness is also limited by the intervention parameter and the water level parameter.

Table 6-3 displays the average roughness after 50 years and Figure 6-3 illustrates these numbers in a graph to make them more comprehensible. Similar to the other parts of the sensitivity analysis, the other parameters are not changed. Therefore, these numbers are the results from model runs without any floods or interventions. The average roughness does not increase when the succession rate is set to a rate larger than 0.3. This means that under those settings all the cells that are affected by the succession rate parameter are completely covered by forest after 50 years.

Because the 'roughest' vegetation group has a value of 0.15, the maximum possible average roughness would be 0.15. The average RV in table 6-3 does not get close to this number for two reasons: a number of cells is not affected by the succession rate setting as these are simulated conform the succession matrix and a significant part of the area already has RV of 0.3 and does not change into any other vegetation type during the simulation run.

Succession rate	Average RV after 50 years
0	0.070
0.1	0.071
0.2	0.077
0.3	0.080
0.4	0.080
0.5	0.080
0.6	0.080
0.7	0.080
0.8	0.080
0.9	0.080
1	0.080

Table 6-3: The average roughness with different succession rate settings.

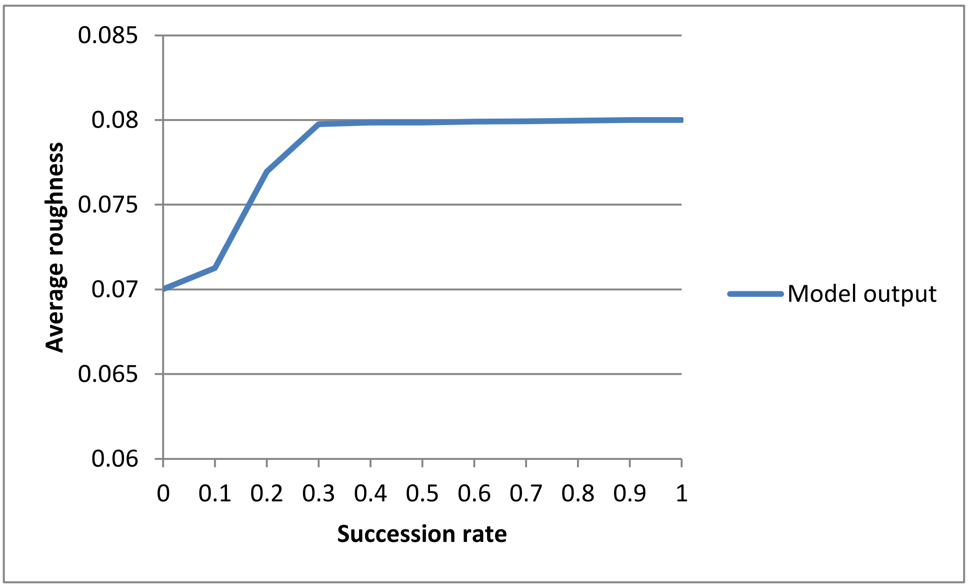

Figure 6-3: Average roughness with different succession rate settings.

The sensitivity of the vegetation sub-model to the other sub-models was measured as well. Table 6-4 and figure 6-4 contain the results from adjusting the water level. The numbers show that there is not a lot of difference in the results with a WL lower than 0.5. Around a WL of 0.75 the average roughness increases slightly. With a WL higher than 1 the average roughness decreases almost linearly.

The increase in average roughness around a WL of 0.75 might be caused by the effect of floods that all succession stages of the succession matrix in flooded cells are reset. As a result these cells use the user defined succession rate, which is higher than the rate of the cells that follow the succession matrix. At higher water levels this effect is negated by the more frequent disturbances caused by floods.

WL	Average RV
0	0.070
0.5	0.070
0.75	0.070
1	0.070
1.5	0.066
2	0.062

Table 6-4: Average roughness with different water levels.

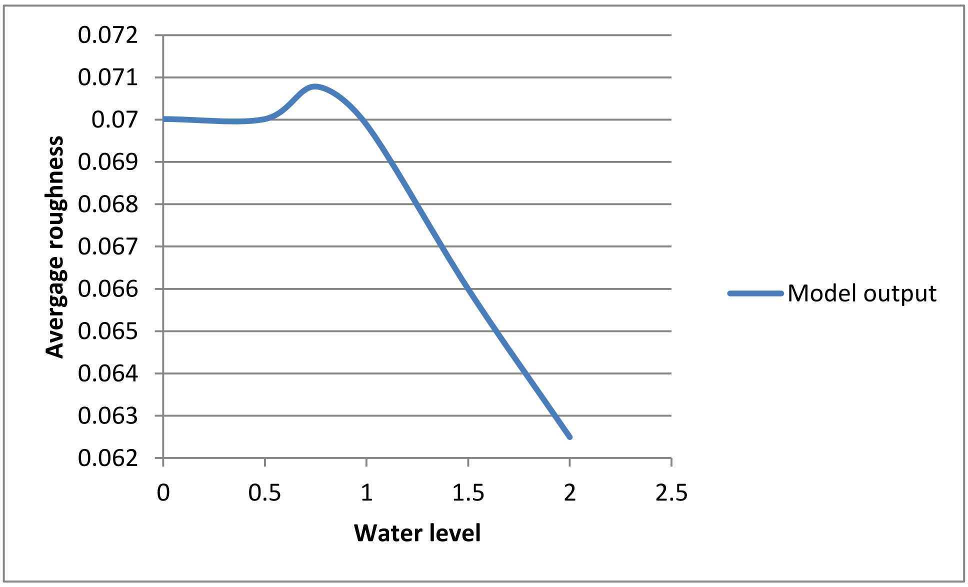

Figure 6-4: Average roughness with different water levels.

The effects of varying the intervention parameter has been measured as well. These measurements are shown in table 6-5 and figure 6-5. The average roughness remains stable up to an area size of 7 hectares. The reason for this is that, only at 7 hectares or more, the number of interventions decreases, as was shown in the sensitivity analysis of the interventions. At even larger area sizes the roughness increases, because intervention occur less frequently. The decrease at 9 hectares might be caused by timing of the final intervention. If the final intervention occurred just before the end of the 50 years, the average roughness would be lower.

IA	Average RV
0	0.058
1	0.058
2	0.058
3	0.058
4	0.058
5	0.058
6	0.058
7	0.058
8	0.058
9	0.058
10	0.058

Table 6-5: The average roughness with different limits to roughness.

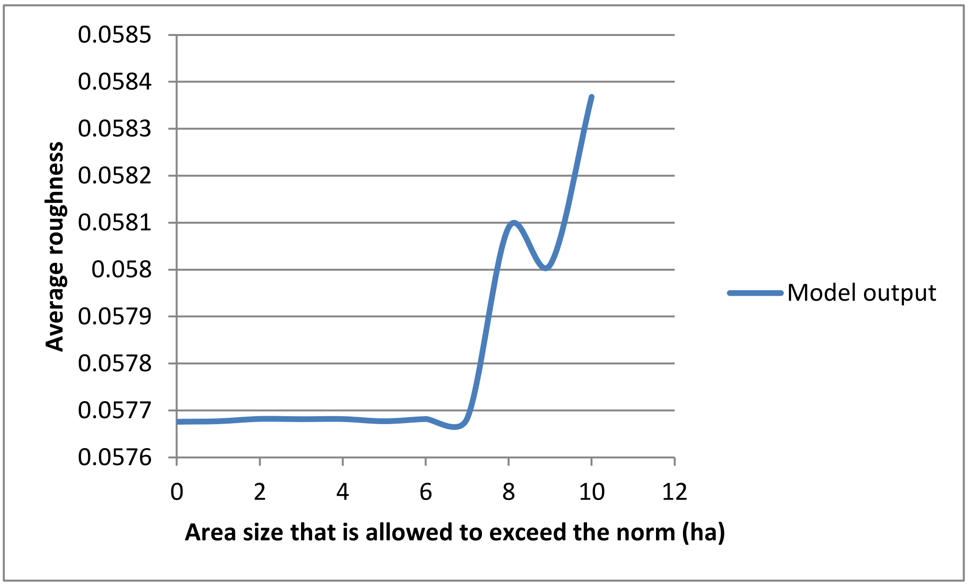

Figure 6-5: Average roughness with different limits to roughness.

6.3. Calibration

Before the scenarios can be simulated by the model the succession rate parameter had to be calibrated. This is done by examining the succession matrix of Peters (2002). While the exact succession rate varies per succession path and stage, the matrix is used to create a rough estimation of plausible succession rates per vegetation type.

Because not all vegetation groups appear in all succession paths, different parts of the succession matrix were used for the calibration. A few rules were used to choose what part of the succession matrix was used for the calibration of each vegetation group:

- The succession path that is used to calibrate the succession rate of a vegetation group must contain a decrease in the percentage of its size. Only in this case, calibration of the succession rate of the vegetation type is possible.
- Preferably a path that does not contain any increase of the vegetation type that has to be calibrated is used. If that is not possible, the increase in vegetation is ignored. The reason for this is that succession rate in the model is measured as a decrease as well. Furthermore, in a path where a vegetation group increases, the growth may be larger than the decrease, resulting in a negative succession rate.
- If a choice has to be made between the three different heights in the succession matrix (low, middle and high), the high succession path is preferred as the land in the research area is for the largest part located on this elevation level.
- The initial stage of succession is ignored, because for most paths the percentages are unknown. The exception to this is grasslands.
- The pioneer vegetation group does not appear in the succession matrix. It is assumed that pioneer vegetation has the same succession rate as bare soil. Forest does not decrease anywhere in the succession matrix and is often part of the final succession stage. Therefore, this vegetation group does not decrease over time.
- For each stage included in the calibration the decrease per month is calculated. The resulting numbers are averaged to determine the succession rate that will be used in the model.

Using these rules the succession rate for each vegetation group was determined as displayed in table 6-6. This table also shows the succession path that was used for the calibration with its corresponding number.

Vegetation group	Succession rate	Succession path used
Bare soil & pioneer vegetation	0.0278	High pioneer situation path (1)
Grass	0.0417	High grassland path (3)
Swamp	0.0556	Low pioneer situation with stagnant environment (1b)
Herbs	0.0866	High agricultural fields (2)
Shrub	0.0417	Low agricultural fields (2)

Table 6-6: The calibrated succession rate of the vegetation types.

To clarify the succession rate calibration more, the calibration on grass will be explained here. The high grassland succession path is used for this calibration, in which grass has the following values:

- 100% grass at year 0
- 80% grass at year 20
- 60% grass at year 100
- 50% grass at year 140

With these values the following succession rates can be determined:

- -0.083% decrease per month for the first 20 years ($\frac{-20\%}{240\ months} = -0.083\%$)
- -0.021% decrease for the 80 following years ($\frac{-20\%}{960\ months} = -0.021\%$)
- -0.021% decrease for the final 40 years ($\frac{-10\%}{480\ months} = \ -0.021\%$)

Averaging these three values results in the average succession rate over 140 years: 0.0417. The calibration of the other vegetation types is performed with the same method.

The intervention parameter is not calibrated as data on interventions is very limited. This is caused by the fact that these interventions are relatively new and do not occur often. The water level parameter is also not calibrated as the unaltered water level is derived from data. Altering the parameter is designed for examining the effects of either a higher or lower water level in scenarios.

Validation of the model is not possible because there is a lack of numerical data on vegetation. However, there is a series of datasets available on the ecotopes of the floodplains in the Netherlands for three different years. The first one of these datasets covers the same year as the data used in the model (1996). However, translating the ecotopes to percentages of vegetation types was not possible, because the datasets had different borders between classes. This means that the ecotope map had classes that covered a variety of different vegetation compositions. It was therefore impossible to use the ecotope datasets for validation.

6.4. Scenarios

With the calibration of the succession rate parameter, different scenarios can be formulated to investigate the effects the parameters have. Similar to the sensitivity analysis, all scenarios are simulated 50 times to come to a stable average of the results of the model. The following scenarios will be discussed in this section:

- Standard scenario
- Altered water level distribution scenarios
  - Half water level distribution scenario
  - Double water level distribution scenario
- No interventions scenarios
  - Normal water level scenario
  - Half water level scenario
  - Double water level scenario
- Altered intervention parameter scenarios
  - Intervention when 7 hectares exceed norm
  - Intervention when 10 hectares exceed norm
- Altered succession rate scenarios with floods
  - Half succession rate scenario
  - Double succession rate scenario

These scenarios will be discussed with tables and maps on the roughness values. Appendix C contains the vegetation maps of all scenarios. Since only the largest vegetation type in each cell is displayed, smaller changes are not visible and differences between some scenarios are difficult to see on these maps. Therefore, in this section only the maps on roughness will be displayed.

6.4.1. Standard scenario

In the first scenario the parameters are set to their 'standard' values. This means that ecological succession will proceed as listed in table 6-6, the floods are not altered and the Rijkswaterstaat intervention agent will intervene when 1 hectare has exceeded its norm. The results from other scenarios are compared with the results from this standard scenario.

Table 6-7 contains the results of the standard scenario. Three vegetation types have a significantly larger RV than the remaining groups: bare soil, grass and forest. There are different causes for the relatively large sizes of each of these types. The high value for bare soil (25%) is caused by the floods that occur regularly. With a normal water level parameter, a lot of vegetation is replaced with bare soil. Grass has a high value (19.8%) because of the annual interventions. During the interventions other types of vegetation are replaced with grass. Forest has a large size (19.9%) because it cannot be removed by floods and succession cannot change forest into another vegetation type.

Outputs	Values
Average RV	0.058
Bare soil (%)	25.05
Pioneer vegetation (%)	0.68
Grass (%)	19.8
Herbs (%)	1.28
Swamp (%)	2.13
Shrubs (%)	4.65
Forest (%)	19.9
Flood frequency	433
Intervention frequency	50

Table 6-7: The results of the standard scenario.

Figure 6-6 shows the distribution of the roughness on a map of one of the model runs in the standard scenario. A few things have a clear link with the starting situation. The areas with the highest RV are generally the locations that started out with a high percentage of forest (see figure 1-2). The lowest class consists mostly of water cells.

However, the starting situation is not the only influencing factor. The most western area is slightly rougher than its surroundings due to a more flexible norm. Interventions only take place in cells with this norm when 20% of the cell is covered by rougher vegetation types.

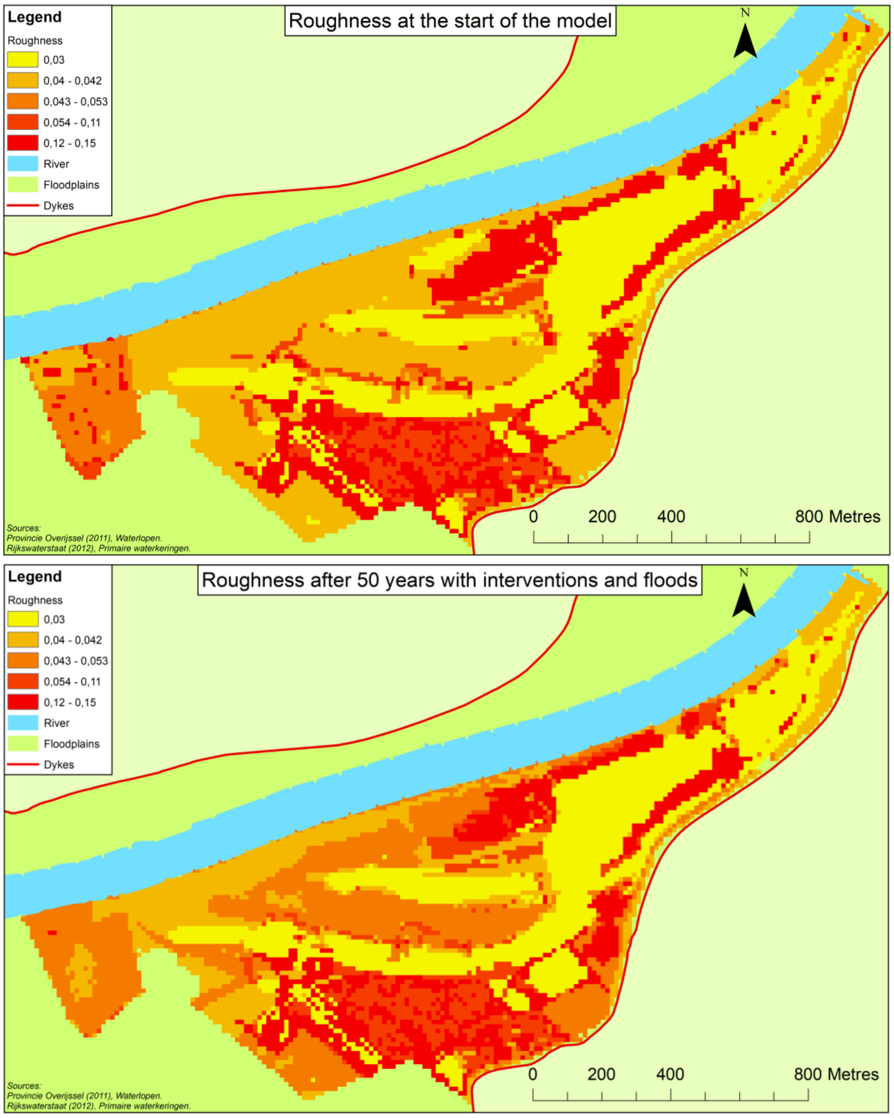

Figure 6-6: Roughness at the start of the model and after 50 years in the standard scenario.

6.4.2. Altered water level scenarios

Two scenarios only differ from the standard scenario in the water level parameter. In one scenario this parameter is set to half the normal water level. The other scenario is set to apply double the water level, which is still limited to 1.89 times the normal water level.

Table 6-8 shows that the impact of a lower water level on the average roughness is minimal (0.059 versus a default value of 0.058), while the effect of increasing the water level is also small. This is conform the findings of the sensitivity analysis on the impact of the WL on the average roughness. The result is striking nonetheless, since the sensitivity analysis also showed that decreasing the WL had a larger effect on the flood frequency than increasing it. A reason for these results might be that inundation does not occur as often in the growing season with a normal water level. The increased water level could cause more frequent floods in the spring, lowering the average roughness.

	Half normal water level	Standard scenario	Double normal water level
Average roughness	0.0589	0.058	0.0560
Bare soil (%)	1.85	25.05	41.73
Pioneer vegetation (%)	0.88	0.68	0.51
Grass (%)	41.45	19.8	5.06
Herbs (%)	2.26	1.28	0.33
Swamp (%)	2.00	2.13	2.49
Shrubs (%)	5.51	4.65	3.60
Forest (%)	18.82	19.9	19.07
Flood frequency	54	433	575
Intervention frequency	50	50	50

Table 6-8: The results of the altered water level scenarios compared to the standard scenario.

While the differences in average roughness may not seem that large, the size of some of the vegetation groups has changed significantly in comparison with the standard scenario. The bare soil class varies a lot between the three scenarios. With double the WL the bare soil class has almost doubled as well (41.7% versus 25% in the default scenario), while with a low WL a large part of this class is replaced by grass (grass covers 41.45%, while bare soil only covers 1.85%). This demonstrates that the size of the bare soil class is heavily dependent on the flood frequency.

The large effect of the WL parameter is also visible on the maps in appendix C. Even in the standard scenario a large number of the cells in the study area has bare soil as largest class. This leaves the impression that either succession or flood damage needs to be further developed to simulate more realistic results, as it seems unrealistic that floodplains consist of such a large percentage of bare soil.

In figure 6-7 the two resulting maps from the scenarios are displayed. The scenario with half the WL has more roughness in most areas. However, this is not the case in the entire research area. There is a small area between the river and the other body of water that has a higher roughness in the scenario with double the WL. There are multiple possible explanations for this result. It could be caused by a lower intervention frequency in that particular area. While table 6-8 shows that the higher water levels did not lead to less interventions while the other parameters remain the same, the number of interventions in that area could be lower due to the norm that is applied there. Another explanation could be that this area is less often inundated than the surrounding area. This could give the area the chance to generate vegetation types with a higher RV that are also more resistant to flood disturbances.

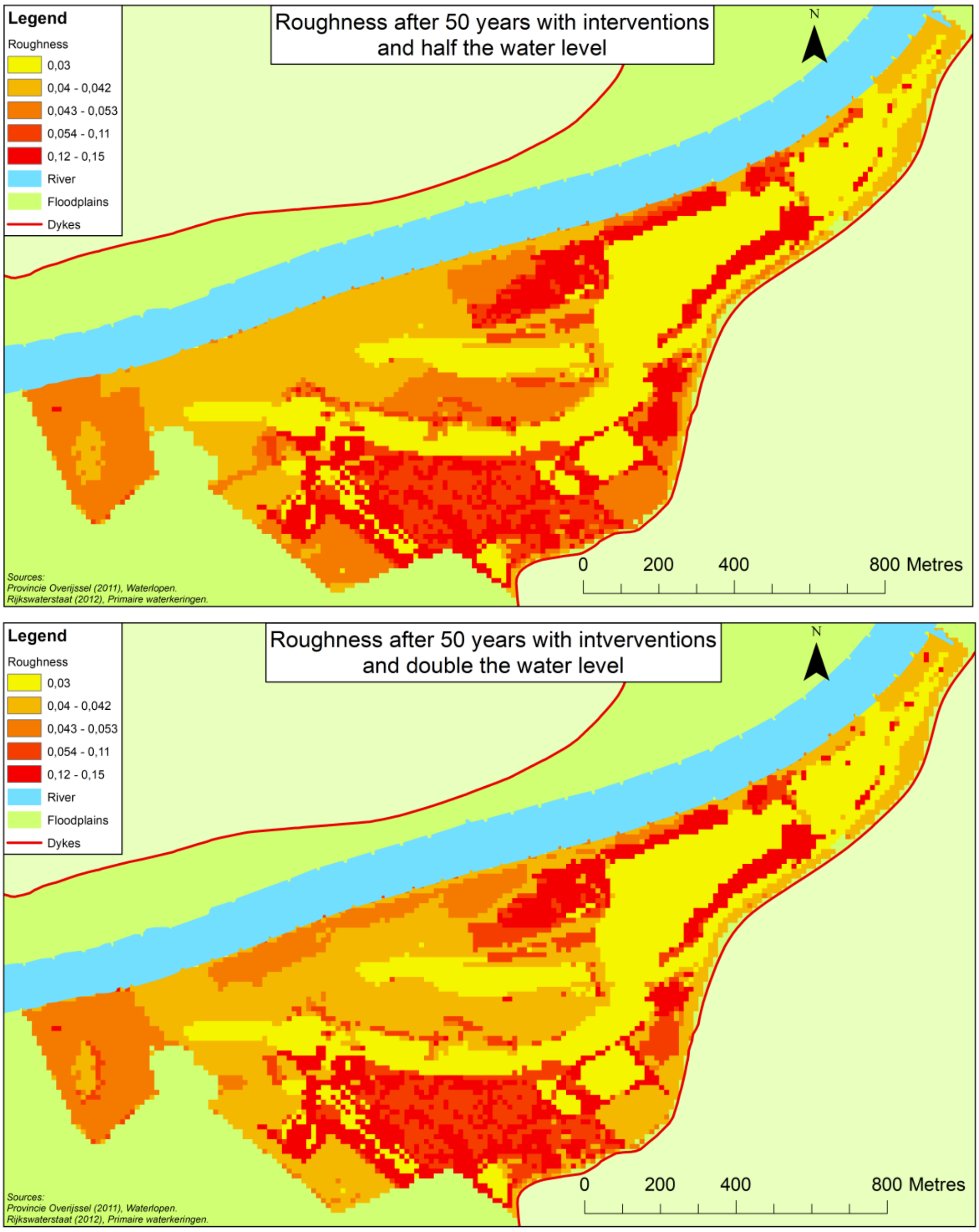

Figure 6-7: Roughness after 50 years in the scenarios with altered discharge distributions.

6.4.3. No interventions scenarios

This section covers three sub-scenarios without interventions and a varying water levels: no altered WL, half the normal WL and double the WL. The results of these scenarios can be found in table 6-9 and figures 6-8 and 6-9.

	Normal water level		Half normal water level		Double water level	
	Interv. (Standard scenario)	No interv.	Interv.	No interv.	Interv.	No interv.
Average roughness	0.058	0.065	0.0589	0.069	0.0560	0.059
Bare soil (%)	25.05	21.51	1.85	0.93	41.73	40.06
Pioneer vegetation (%)	0.68	0.68	0.88	0.93	0.51	0.51
Grass (%)	19.8	11.75	41.45	25.43	5.06	3.72
Herbs (%)	1.28	3.81	2.26	5.95	0.33	0.52
Swamp (%)	2.13	2.47	2.00	2.31	2.49	2.97
Shrubs (%)	4.65	8.95	5.51	15.61	3.60	3.83
Forest (%)	19.9	23.43	18.82	21.42	19.07	21.12
Flood frequency	433	433	54	54	575	575
Intervention frequency	50	0	50	0	50	0

Table 6-9: The results of the no interventions scenarios compared to other scenarios.

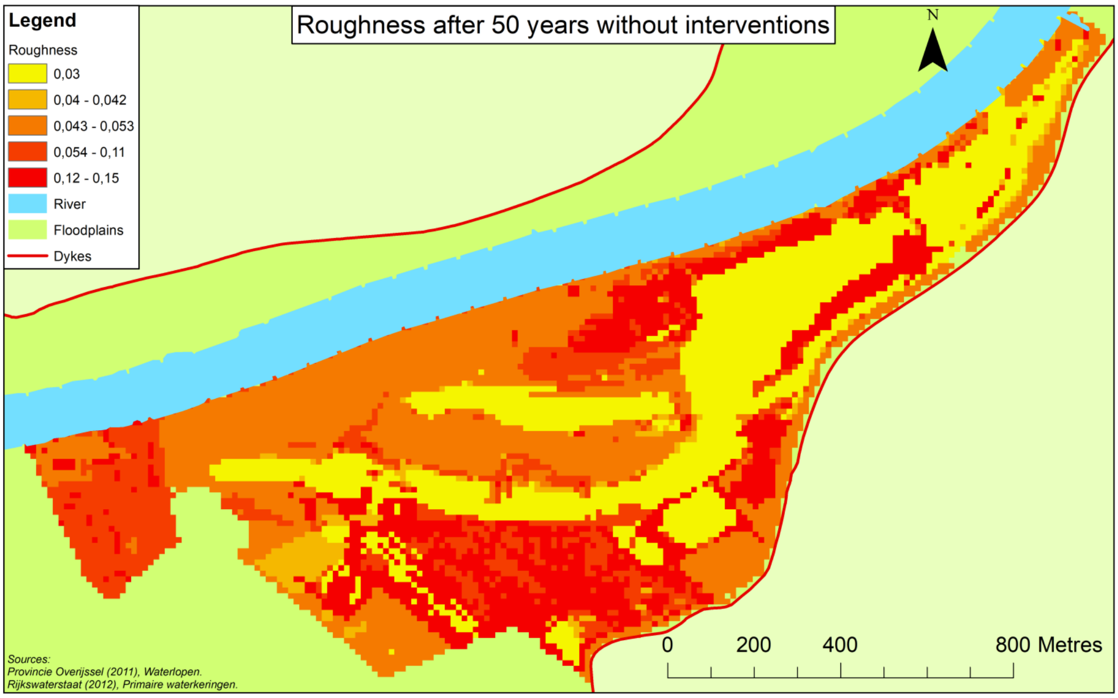

Figure 6-8: Roughness after 50 years in the no interventions

The simulations without interventions lead to a higher roughness as there are no more limitations to the vegetation groups. Without the limitations of the interventions, ecological succession has progressed further. The higher RVs are still concentrated in the same areas. However, a large part of the cells that were in the 0.04-0.042 roughness class in the standard scenario ended up in a higher roughness class in the no interventions scenario, most notably in the area between the river and the other water cells.

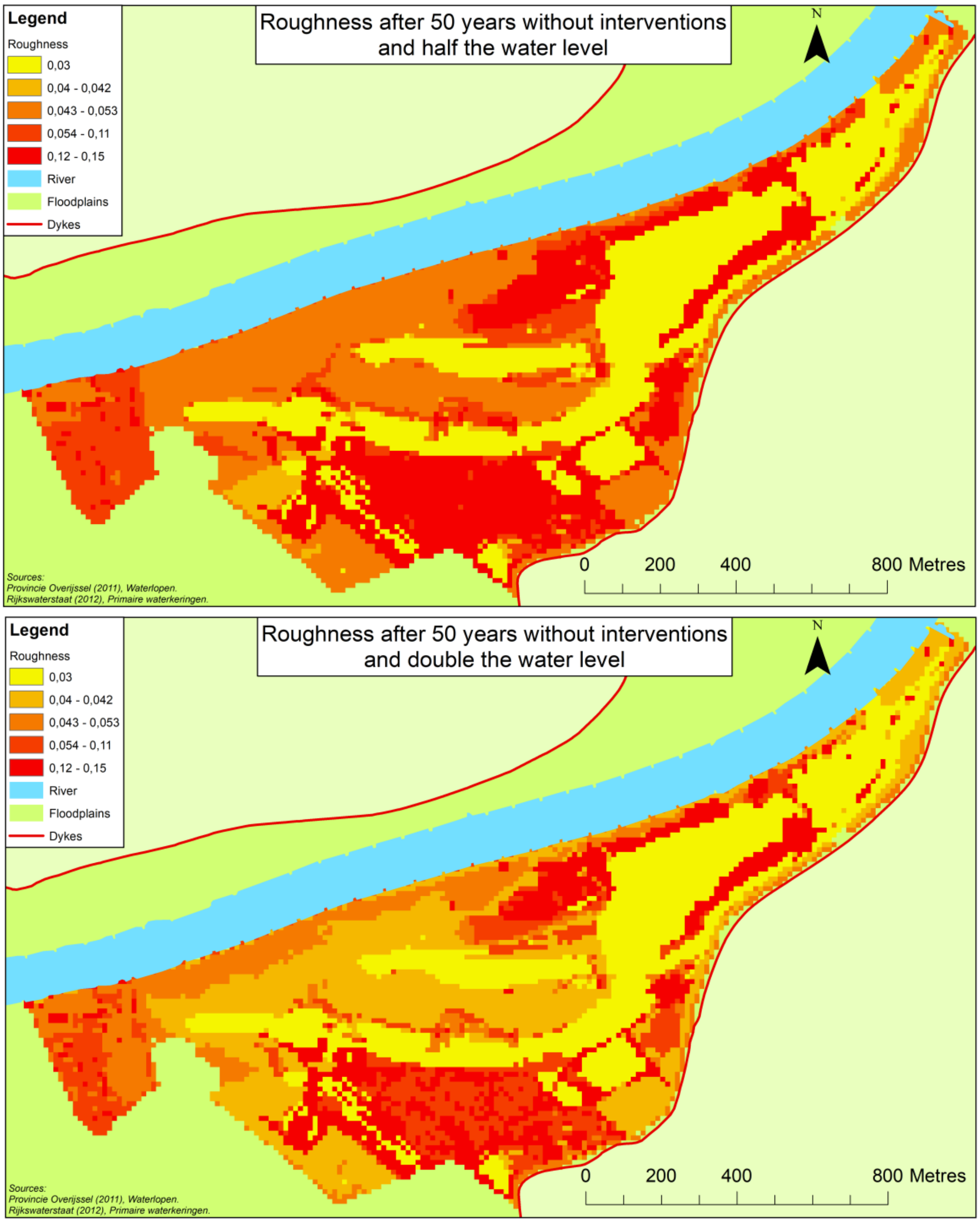

Figure 6-9: Roughness after 50 years in the no interventions scenarios with altered water levels.

Not only the roughness is affected by the lack of interventions, but the vegetation groups are different in size as well. Grass is 10% smaller without interventions, confirming the assumption in the previous section that a large part of the grass land cover was caused by interventions. Bare soil also has decreased in size, due to the fact that a larger percentage of the vegetation reaches the shrubs or forest stage. In these succession stages the vegetation the effect of floods is lower.

In the no interventions scenario with only half the WL, the roughness is only slightly higher than with normal floods. The differences are also not very visible on the map in Figure 6-9. However, large changes do occur between the vegetation groups. The high percentage of bare soil in the normal water level scenario is replaced by high grass and shrubs percentages. This change indicates that a lot of grass and shrubs are located in relatively high areas that are also frequently inundated during the growing season.

By doubling the normal WL, the average RV decreases significantly, to almost the same value as in the standard scenario (0.059 and 0.058 respectively). Due to the frequent floods, the vegetation is unable to develop further. As a result, most vegetation types remain very small. Similar to the scenario with interventions and double the flood frequency, the roughness of the area between the main river and the rest of the water looks like the opposite of the standard scenario. Since there are no interventions in this scenario, it is likely that the area with higher roughness in both scenarios with doubled water levels is caused by the spread of inundation during the growing season.

6.4.4. Altered intervention parameter scenarios

In the sensitivity analysis was shown, that the intervention parameter only has an effect on the intervention frequency when it set to 4 or higher. Two scenarios were tested for this section: one with the intervention parameter set to 7, while for the other, the parameter was set to 10. These parameter values were chosen, because these both resulted in very different intervention frequencies. The results are shown in table 6-10 and figure 6-10.

	Standard scenario	Intervention when 7 hectares exceed norm	Intervention when 10 hectares exceed norm
Average roughness	0.058	0.058	0.061
Bare soil (%)	25.05	25.05	24.25
Pioneer vegetation (%)	0.68	0.68	0.68
Grass (%)	19.8	19.12	15.93
Herbs (%)	1.28	1.26	2.18
Swamp (%)	2.13	2.13	2.16
Shrubs (%)	4.65	4.63	6.59
Forest (%)	19.9	19.9	20.88
Flood frequency	433	433	433
Intervention frequency	50	36	1

Table 6-10: The results of the scenarios with different intervention parameters.

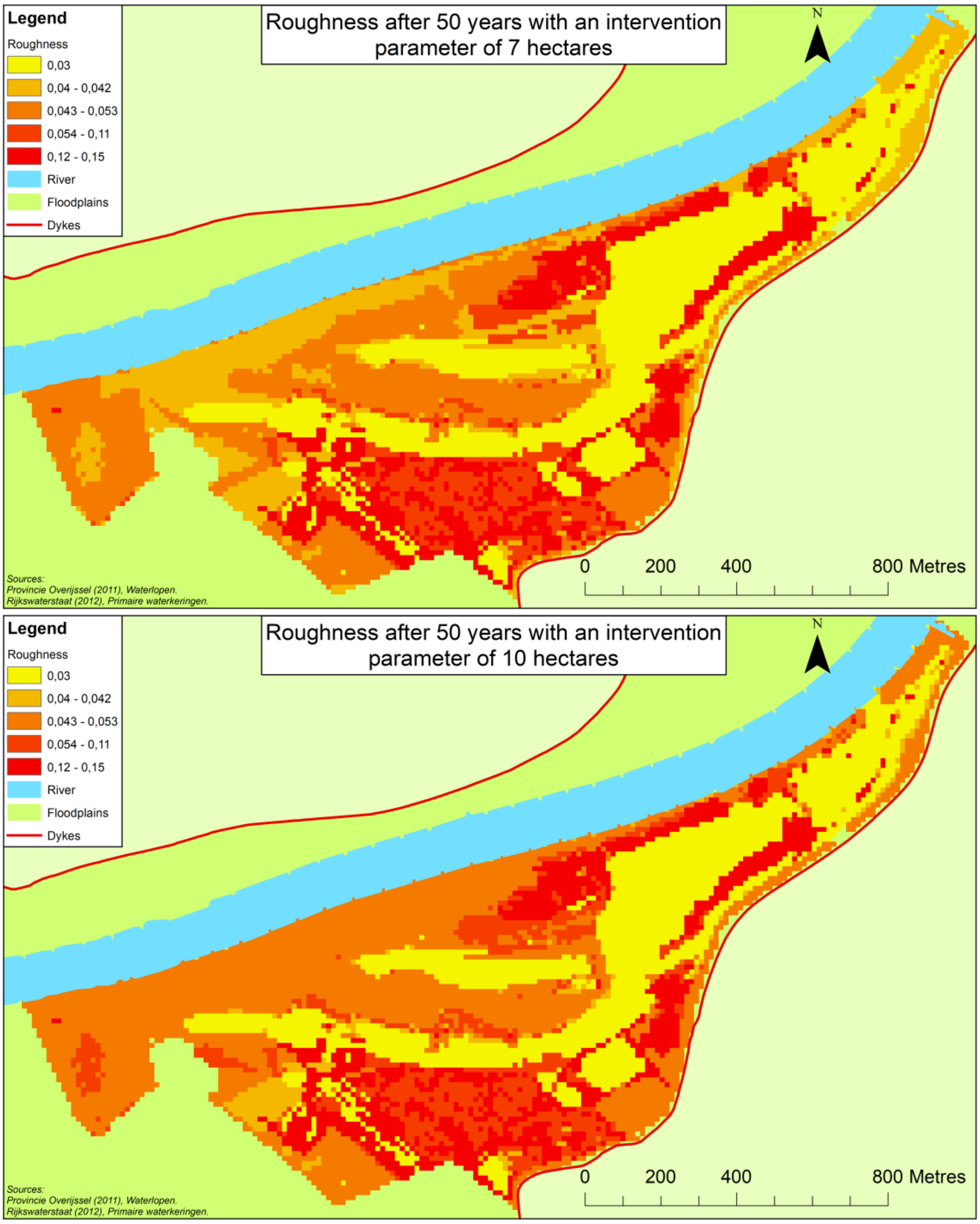

Figure 6-10: Roughness after 50 years in scenarios with different intervention parameters.

When the intervention parameter is set to 7 the changes to vegetation are almost non-existent compared to the standard scenario. The average roughness remains the same and the differences within the vegetation groups are very small as well. The differences between the resulting maps are very small and difficult to spot. From this it can be concluded that only intervening when 7 hectares exceed the norm is more efficient in limiting the roughness than the standard scenario when intervention already occur when 1 hectare exceeds the norm. It only requires 36 interventions as opposed to the 50 interventions in the standard scenario to get a very similar result.

With an intervention parameter of 10, the results are slightly different. Grass decreases in size (15.9%), while the area covered by shrubs becomes slightly larger (6.6%). This is also reflected in a higher average roughness. This increase in roughness is more noticeable on the map, as a large part falls in a higher roughness class. Despite the small differences in average roughness, the intervention frequency has been reduced to merely one intervention. This is even lower than tested in the sensitivity analysis due to the lower succession rate and the effect of floods in this scenario.

6.4.5. Altered succession rate scenarios

The final two tested scenarios include changes to the succession rate parameter. The options for these parameters are almost endless. To limit the amount of results, only two scenarios were chosen, similar to the water level scenarios: half the normal succession rate and double the succession rate.

	Standard scenario	Half succession rate	Double succession rate
Average roughness	0.058	0.056	0.061
Bare soil (%)	25.05	26.87	23.15
Pioneer vegetation (%)	0.68	0.69	0.65
Grass (%)	19.8	18.64	19.30
Herbs (%)	1.28	1.54	1.17
Swamp (%)	2.13	2.37	1.73
Shrubs (%)	4.65	4.56	4.69
Forest (%)	19.9	18.12	22.08
Flood frequency	433	433	433
Intervention frequency	50	50	50

Table 6-11: The results of the scenarios with different succession rates.

Table 6-11 shows that cutting the succession rate in half does not have a large impact on the roughness, as it only decreases slightly. Furthermore, the changes in the vegetation groups are small as well. Increasing the succession rate has a larger effect, but this is still not as large as the impact of some of the other scenarios that were tested. A noticeable similarity between increasing an decreasing the succession rate is that both result in a lower roughness in the area between the river and the other water cells. In the halved succession rate scenario this could be caused by the slower succession rate. In the doubled succession rate scenario the high succession rate might have caused more interventions in that area that did not occur in the standard scenario. Despite the lower roughness in that particular area, the double succession rate scenario still results in a higher average roughness. Figure 6-11 shows that this higher roughness is likely to be the result of the succession in the southern area as some parts there have a higher roughness class than in the standard scenario.

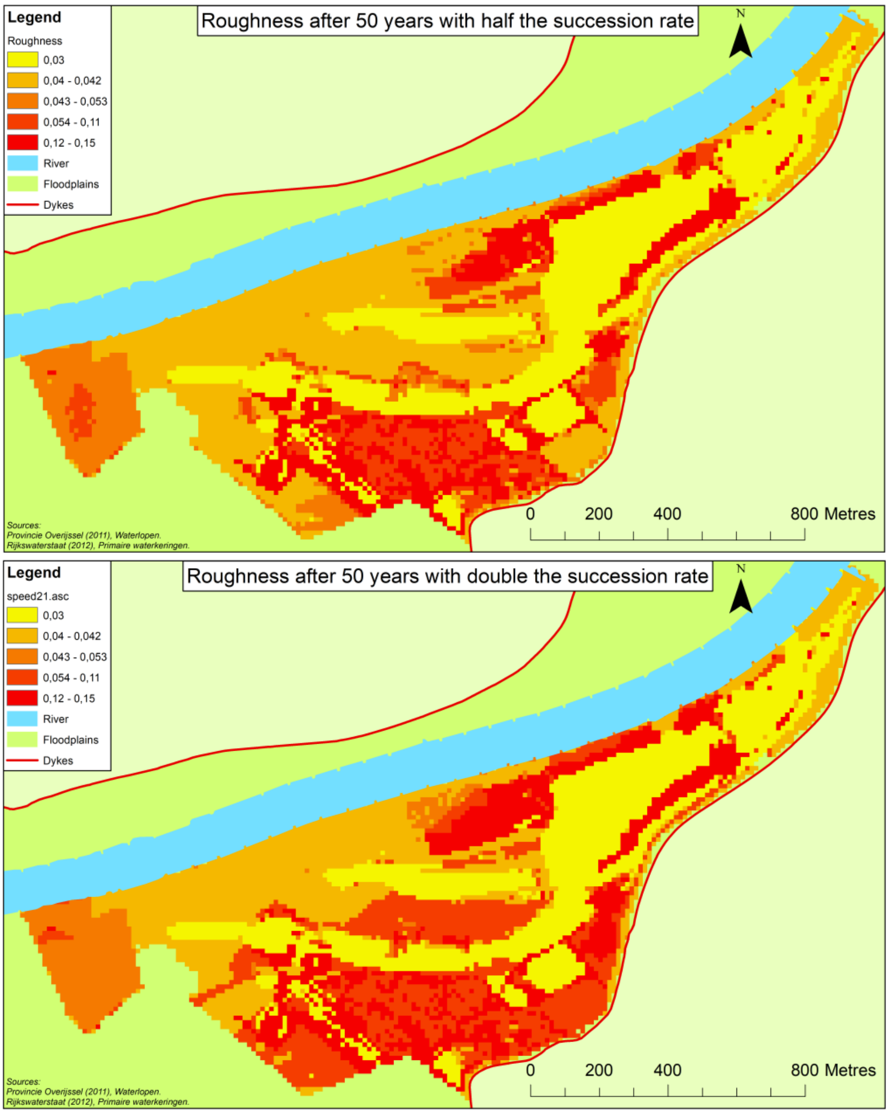

Figure 6-11: Roughness after 50 years in scenarios with different succession rates.

7. Conclusions and discussion

7.1. Conclusions

The goal of this research was to develop an agent-based model for vegetation development in river floodplains in order to determine the impact of changing water levels on vegetation management.

The first step to achieve this was performing a literature review on vegetation development, vegetation models and flood models. Based on the knowledge gained during this literature review a model design was designed, consisting of a new vegetation model and intervention model, integrated with an existing flood model. This model design was then used to develop a prototype. With these research steps the main research question can be answered. The main research question was:

How can an agent-based model be created that can be used to evaluate the impact of changing water levels on the vegetation development in river floodplains and its management?

There are three major components that influence vegetation development in the floodplains: succession, floods and interventions. Each of these components plays a different role in vegetation development. Succession increases roughness by altering the vegetation types that are present in the floodplains. Floods and interventions are both disturbances that can reset and limit this succession process to a certain extent.

With the three major factors and the state-and-transition modelling approach, a prototype of a complete floodplain vegetation model was created. Succession was modelled by combining the succession matrix of Peters (2002) and the succession schemes of Van Velzen (2003). Plant species were grouped together in vegetation types that were also used in the matrix and schemes. The exact succession rate and direction was determined by using the existing vegetation composition and the flood frequency.

Interventions were integrated in the vegetation model by simulating the intervening actor, Rijkswaterstaat, as an agent. This agent determined at what time and location interventions were needed by comparing the Vegetatielegger to the vegetation in the model. The intervention agents also takes the effects of floods on vegetation into account.

There are multiple flood models that could been integrated with the vegetation model. However, in the end a relatively simple flood model was chosen, as the more complex models would require a conversion, which take more time. The complex models would also require more data as input. The chosen flood model was integrated by removing vegetation in flooded areas under specific circumstances, such as during the growing season.

By integrating the sub-models, the main model was finished and ready to be tested. In the sensitivity analysis and in the scenarios it was discovered that the flood frequency was more affected by a decrease in water level than an increase. However, an increase had a larger effect on the roughness than a decrease. This means that a large part of the research area was located at a higher elevation than the height of most floods in water level dataset. Higher water levels in the river could therefore lead to a lower intervention frequency.

The sensitivity analysis also demonstrated the large impact floods and interventions have on specific vegetation types. A high water level leads to significantly more bare soil, while a large number of interventions leads to large increase in grass. Since both interventions and floods reduce roughness, increasing the water level in the river might be a way of reducing roughness without intervening in the area itself. It also shows the significance of the impact of these disturbances on the vegetation types. In the current prototype, floods and interventions replace vegetation with bare soil and grass respectively. If the impact of these disturbances was set to pioneer vegetation instead for example, the pioneer vegetation type would be large in scenarios with many interventions or floods. Because these two disturbances influence the vegetation composition of the research area to a large extent, it is important to consider what effect these disturbances have on the vegetation types while creating a vegetation model. However, it is difficult to design appropriate effects for these disturbances, as the exact impact is often unknown.

While the scenarios proved that interventions have a large impact on the vegetation composition, it also showed that with a low intervention frequency and normal floods, the roughness does not increase significantly. Even with only one intervention the roughness was hardly higher after 50 years than with 50 interventions. Because the roughness was measured only after 50 years of the simulation, it is possible that somewhere in the simulation the floodplains had a much higher roughness in the scenarios with lower intervention frequencies. However, it seems more likely that the intervention occurred in the first year and that succession process was not quick enough to cause another intervention within those 50 years. The small impact of interventions on the roughness proves that the annual interventions in some scenarios are unrealistic.

7.2. Limitations of the current study

7.2.1. Data limitations

One of the major difficulties in the creation of the model was the lack of numerical values for model parameters in literature. The impact of floods was a prime example of this. Knowing that floods damage and destroy vegetation is useful, but integrating this effect into a model is complicated without any numbers. The model was first set to remove any inundated vegetation. This appeared to be too devastating and the impact of floods had to be altered. By examining the timing of floods, the flood depth and the vegetation types, the impact of floods was decreased.

Unfortunately, validating the model was not possible, because of the lack of similar vegetation data. Since the model used vegetation data in percentages, data for validation would need to include percentages for different dates as well. The only vegetation data available for the research area consisted of ecotopes that could not be translated into numerical values. However, because the model is merely a prototype it is likely that more factors would need to be included to create better results.

The lack of numerical values is therefore one of the suggestions for further research. On the one hand numerical data is needed on vegetation compositions for different years and locations to validate the model. On the other hand numerical data can be a method to calibrate the exact effect of certain events, such as floods. This could lead to improvements in the vegetation model.

7.2.2. Model limitations

The model can be expanded by integrating more processes. One example is the impact of the surface on vegetation, because soil type, soil grain size and soil moisture can have effects on vegetation development. These effects were not included due to the lack of knowledge on the exact impact.

Integrating a different flood model could also be an improvement to the model. The current flood model is relatively simple and does not take into account all the factors that cause floods. Such a flood model could for example utilise data on roughness and flow rate. This would also make it possible to simulate the impact of vegetation on floods, which is currently lacking. However, this does require more data, which may be hard to acquire. Furthermore, because the model simulates events in the future, predictions may have to replace some of the required data.

Finally, the model could be altered to integrate the random nature of vegetation development better. The succession matrix of Peters (2002) is based on mere estimations and there is more randomness involved in vegetation development in reality. The time to reach the next stage of succession could be random as well as the vegetation composition of each stage.

7.3. Discussion

Because vegetation development depend on many factors, choices had to be made. These choices had a large impact on the model and the results derived from that model. Moreover, these choices were not always ideal and other solutions could have been chosen.

One example is the definition of the elevation levels. This definition has a large indirect effect on the results. Not only does it determine the water level that determines a flood, but it also influences the vegetation development. An automated approach was chosen to make it easy for the user to change the water level. In this approach, the water level data is sorted from large to small numbers to determine the elevation levels. Because there is no distinction between years in the model for the water level data, sorting all input would mix the years up. This would result in inaccurate elevation levels. An alternative to create sub-lists for each year of water level data was problematic as well, due to the fact that the water level dataset can vary per user. Therefore, only water level data of the first year of was used in this definition. Because the first year happened to have lower water levels, relatively low water levels were counted as floods. This had a large impact on the results of the sensitivity analysis and the scenarios. Determining the elevation levels manually could have led to more accurate results. Alternatively, the fact that years are mixed up could be ignored and the entire water level dataset could be used for the definition of a flood. While this would still lead to inaccurate elevation levels, it might be the better option than only using the first year.

Another choice influenced the results was the assumption that succession progresses linearly. This is not completely realistic and also caused interventions to occur more often then was intended. There are three ways to prevent these problems or limit their impact. First, succession could be modelled in a non-linear way. By making succession start after a cell has been in a certain stage for a longer time. Secondly, a distinction could be made between the seasons. Succession could progress at a higher pace in the spring, while it could be halted during the winter. Finally, the rate of succession could also be dependent on more factors that vary locally. Soil type and moisture are examples of this that were already mentioned in the conclusion.

Thirdly, at the start of the model creation, the choice was made not to model grazing animals as agents, because in the succession matrix the assumption was made that natural grazing is present. Because the succession matrix was not used for the entire research area, it would be justified to simulate grazing animals in the model. Grazing animals could be modelled as agents. One issue with this is that vegetation changes slowly over many years, while animals can change their location within one single hour. Therefore different time steps would be required.

A fourth significant choice was to model vegetation in percentages instead of ecotopes. Ecotopes appeared to be problematic to use in the model and because the succession matrix also contained percentages, the choice was made to put these to use. This reliance on percentages of vegetation cover caused some problems as well. One problem was that it is difficult to visualise within the model. Only the largest vegetation type per cell is displayed, while the smaller ones are invisible. Since the monthly changes in vegetation composition are small, the succession process is not very visible. Due to the lack of visualised changes it is difficult to see what is happening in the model. This problem with visualisation also makes the model less interesting to look at.

The used percentages also appeared more precise than they might be in reality. Part of the study area did not have the exact same vegetation composition as in the succession matrix. However, it is unlikely that a cell that has 5% less of a certain vegetation type (compared to the matrix), will develop in a completely different direction. This in turn raised the question how much does a cell in the model need to differ from a succession stage to be part of a completely different succession path. Because no answer was found to this question, the model uses both the succession matrix as well as the schemes.

Finally, inaccuracies in the model could also be caused by the used datasets. Since only limited data was available, some datasets are not from the same year. The used vegetation data is from research conducted in 1996, while the elevation data dates from 2010. As a result some vegetation is at NAP level and is permanently inundated. The vegetation in these areas cannot change, because succession does not progress and interventions do not occur in inundated areas. Simultaneously floods do not remove any of the starting vegetation as these areas are part of the lowest elevation level.

7.4. Recommendation for further work

Because the current vegetation model is merely a prototype, it can be used as an example to develop a fully fleshed out vegetation model in further research. A complete model would integrate the impact of more factors in vegetation development, such as soil type. As more factors are included in a complete model, it is likely that the current flood model would not be sufficient. Therefore, a complete model would also require more research on what flood model is best suited for the complete vegetation model.

Since vegetation development varies a lot between locations, further research could be done on developing similar models for other rivers, climates or landscapes. Due to the different characteristics of other research areas, other types of disturbances would occur and other factors would become more prominent in the succession process. Examining the impact of changing the scale of the model by modelling individual plant species could be a topic for further research as well.

Finally, more research could be done on the impact of floods on the intervention frequency. In the literature review it was stated that inundation causes vegetation to die. As a result, higher water levels in the model led to a lower roughness in the study area. Therefore, in further research it could be examined if higher water levels lead to a lower intervention frequency in reality.

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Appendices

A. Datasources

Source	Dataset
Actueel Hoogtebestand Nederland (AHN), 2010. AHN2 5 meter maaiveldraster. Obtained from: https://www.pdok.nl/nl/producten/pdok-downloads/atomfeeds.	Elevation data
CBS (2011). Bevolkingskernen. Obtained from: https://www.cbs.nl/nl-nl/achtergrond/2014/13/bevolkingskernen-in-nederland-2011.	Location of Wijhe data (for visualisation of results only)
Provincie Overijssel (2011). Waterlopen. Obtained from: https://data.overheid.nl/data/dataset/waterlopen-01.	River data (for visualisation of results only)
Rijkwaterstaat, 1996. Vegetatie- en structuurkaart Duursche Waarden.	Vegetation data 1996
Rijkswaterstaat, 2012. Primaire waterkeringen. Obtained from: https://data.overheid.nl/data/dataset/rws-dijkringlijnen-actueel.	Dyke location data
Rijkswaterstaat, 2014. Vegetatielegger. Obtained from: https://data.overheid.nl/data/dataset/Vegetatielegger-vegetatievlakken.	Vegetation norm data
Rijkswaterstaat, 2017. Waterhoogte Oppervlaktewater t.o.v. Normaal Amsterdams Peil in cm. Obtained from: https://waterinfo.rws.nl.	Water level data

B. Original vegetation map legend

Legend

- Open water
- Open vegetation with calamus
- Covered by European white water lily and yellow water lily
- Covered by water weeds, common duckweed and water starwort

Swamp vegetation

- Swampvegetation with reed canary grass and common nettle
- Swampvegetation with reeds and common nettle
- Swamp dominated by great manna grass, water mint, calamus, acute sedge or great yellowcress

Pioneer vegetation

- Slightly covered by water forget-me-not, creeping yellowcress, needle spikerush, water mudwort and red water-speedwell
- Slightly covered by common silverweed
- Slightly covered by couch grass, Canadian horseweed and wormseed wallflower
- Covered by reed canary grass, European dewberry, various willows and a large number of varying herbs

Grass

- Herbaceous vegetation with water mint, broadleaf plantain, water forget-me-not, purple loosestrife, creeping yellowcress, reed canary grass, common silverweed, creeping bentgrass and white clover
- Homogeneous grass vegetation with couch grass
- Homogeneous grass vegetation with couch grass
- Grass vegetation dominated by creeping bentgrass, couchgrass or rough bluegrass
- Heterogeneous grass vegetation with perennial ryegrass, red fescue, false oat-grass, yarrow, compact dock, field eryngo, yellow bedstraw and yellow lucerne
- Grass vegetation with bushgrass
- Herbaceous grass vegetation with common nettle

Herbaceous vegetation

- Herbaceuous vegetation with European dewberry, couch grass, creeping thistle and common nettle

Low forest

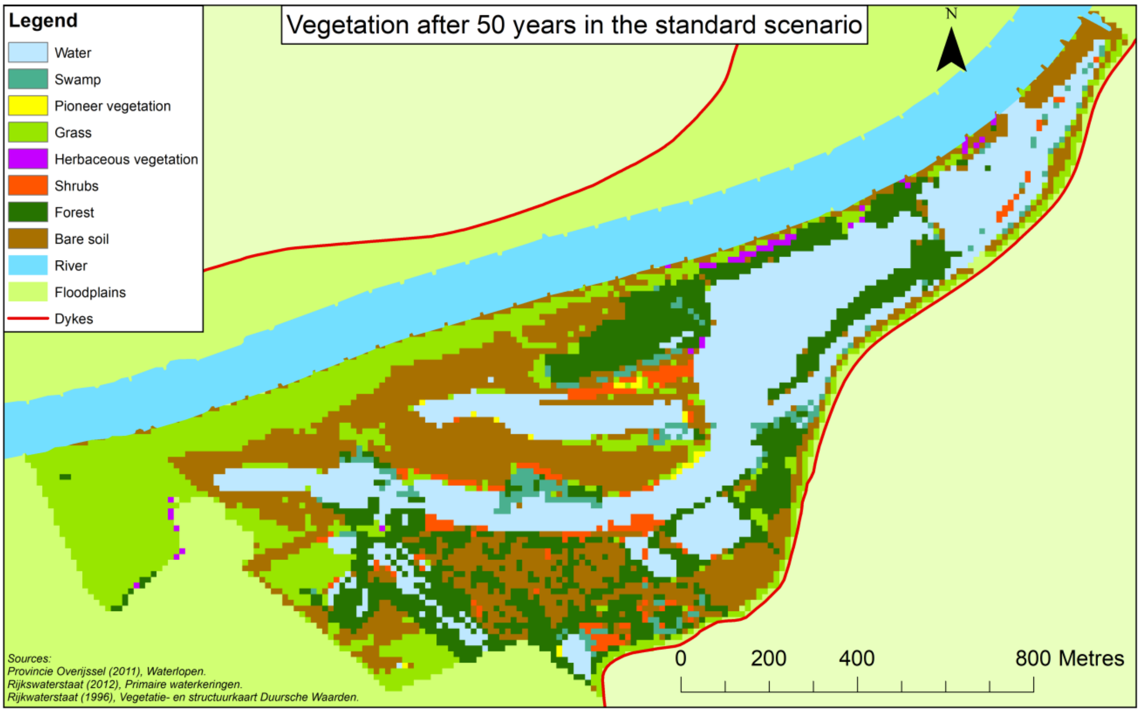
- Young trees consisting of white willow, basket willow and almond willow and a heterogeneous undergrowth
- Older hedges with common hawthorn, blackthorn, dog rose and common ash

Tall forest

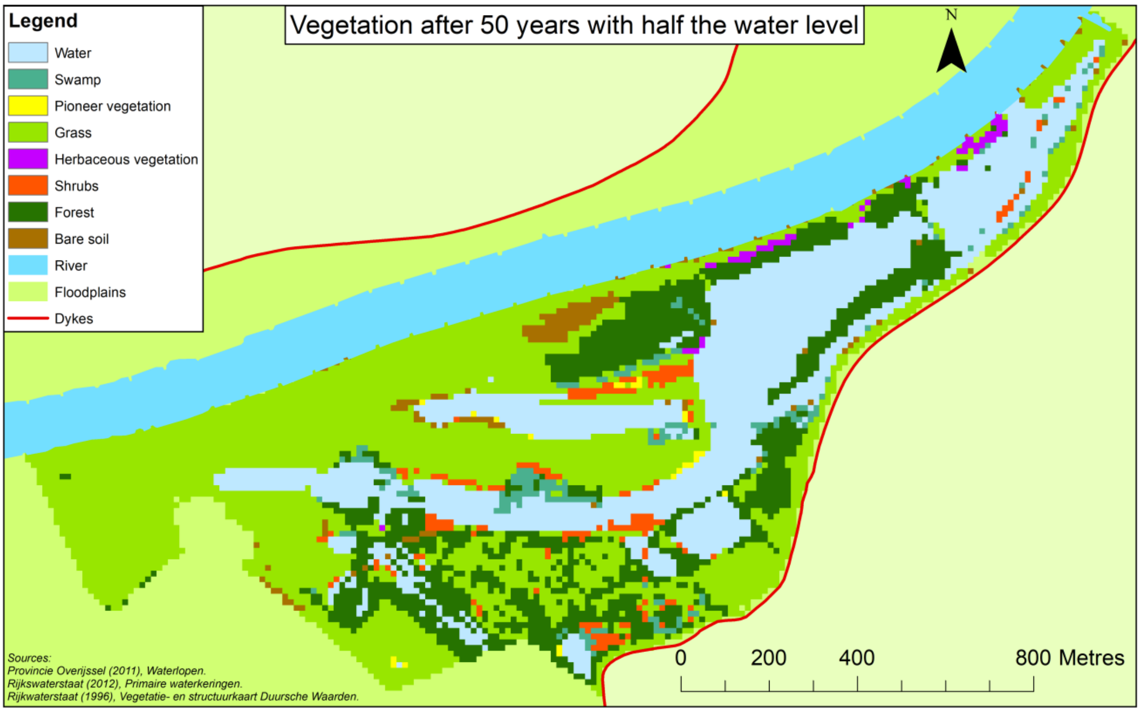
- Forest with common oak and an undergrowth of ground-ivy, common nettle and European dewberry
- Forest with heterogenuous undergrowth
- Forest with Canadian poplar and an undergrowth of European dewberry and reed
- Forest with common ash, common hawthorn and blackthorn with an undergrowth of ground-ivy, European dewberry and common nettle
- Forest with white willow or basket willow with an undergrowth of common nettle and European dewberry

C. Vegetation maps of the scenarios

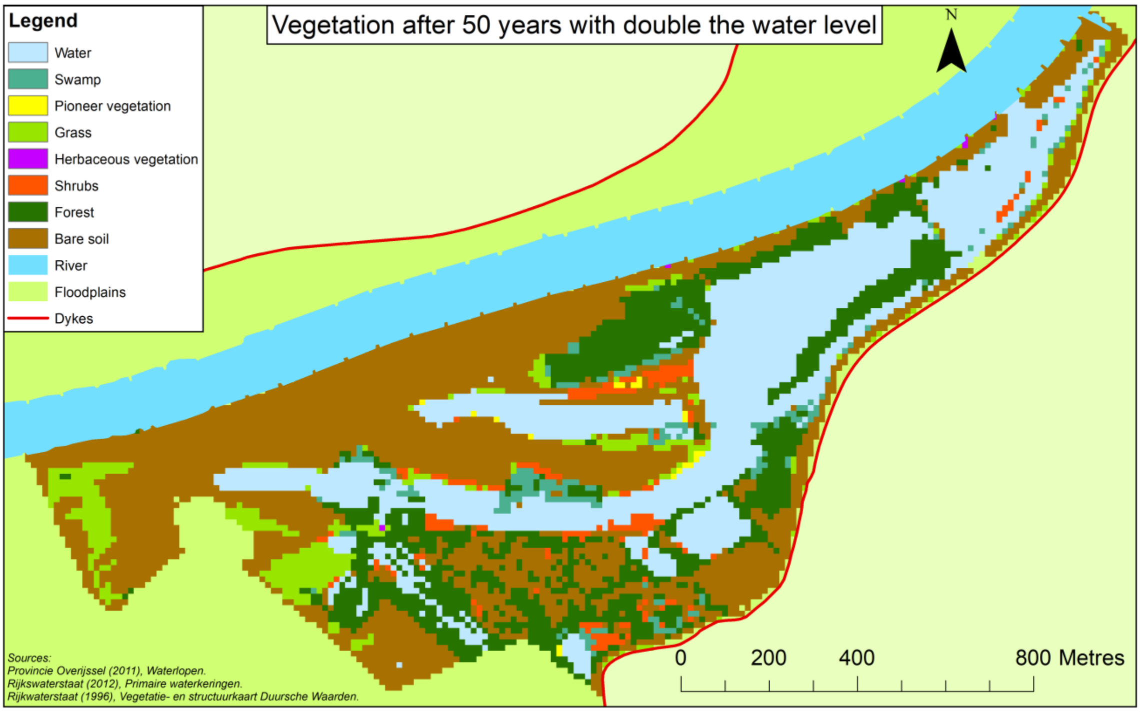
C.1: Vegetation map of the standard scenario.



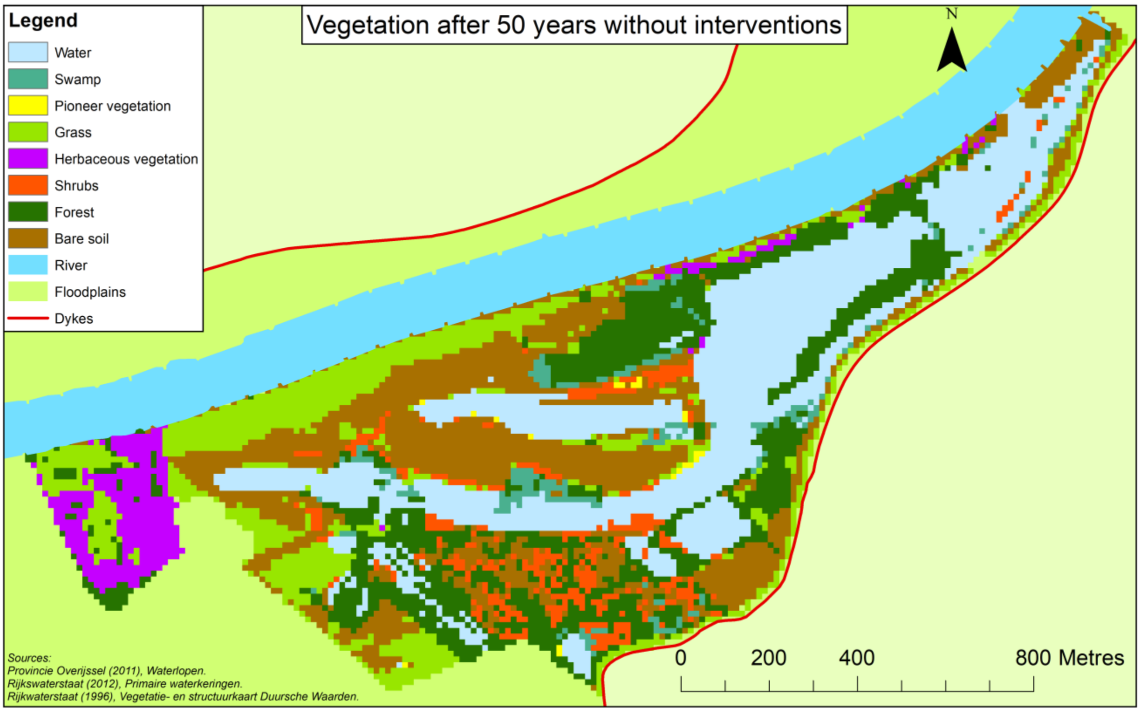
C.2: Vegetation map of the half water level scenario.



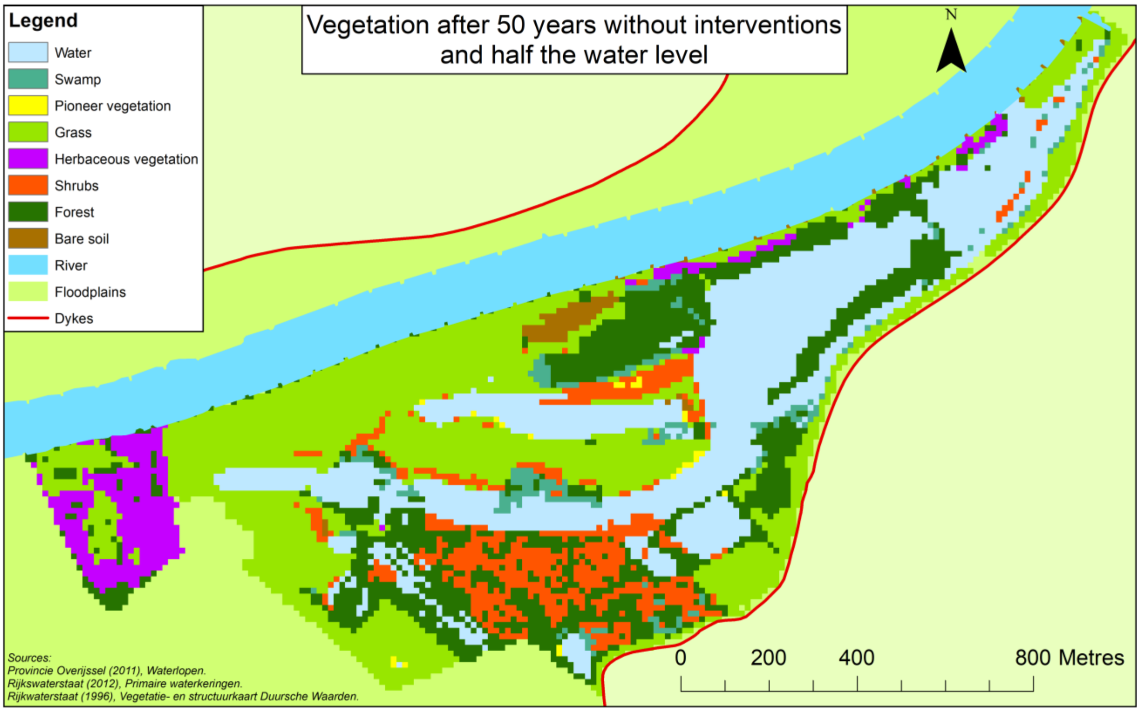
C.3: Vegetation map of the double water level scenario.



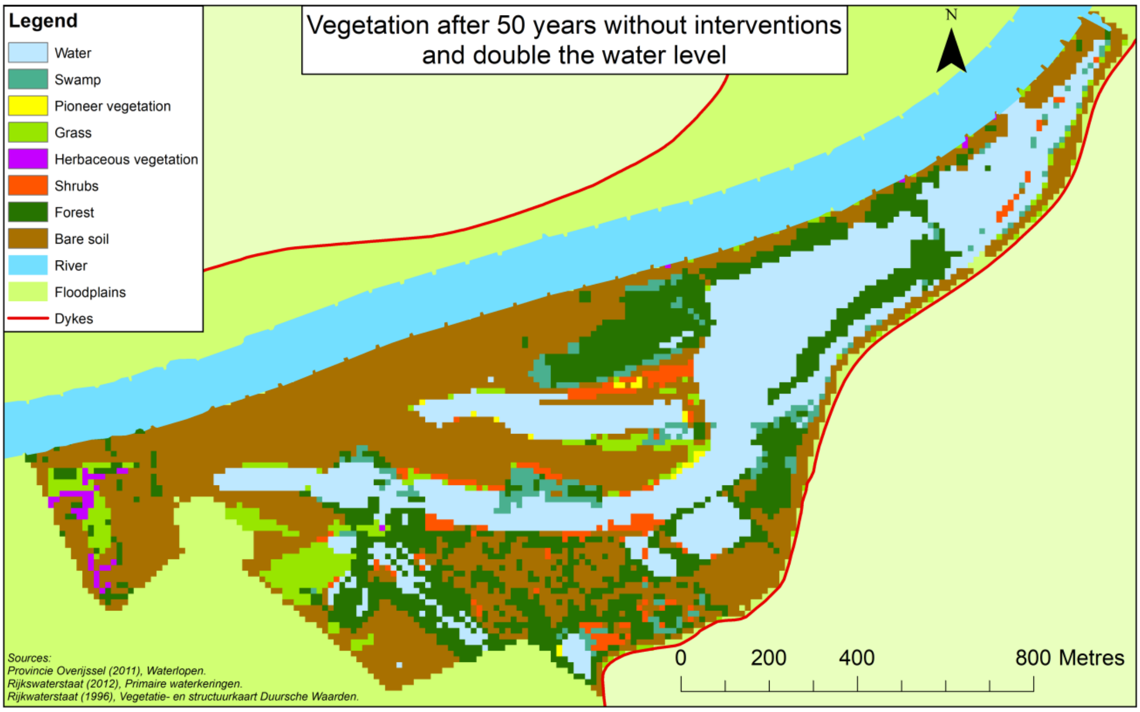
C.4: Vegetation map of the no interventions scenario.



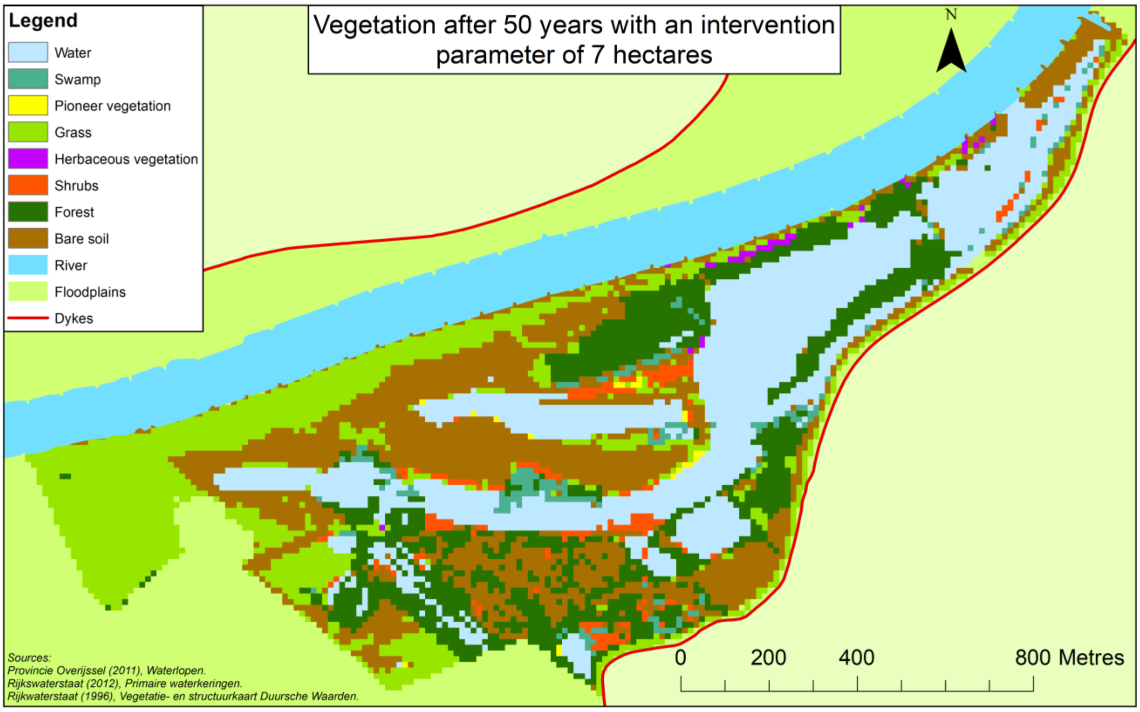
C.5: Vegetation map of the no intervention scenario with half the water level.



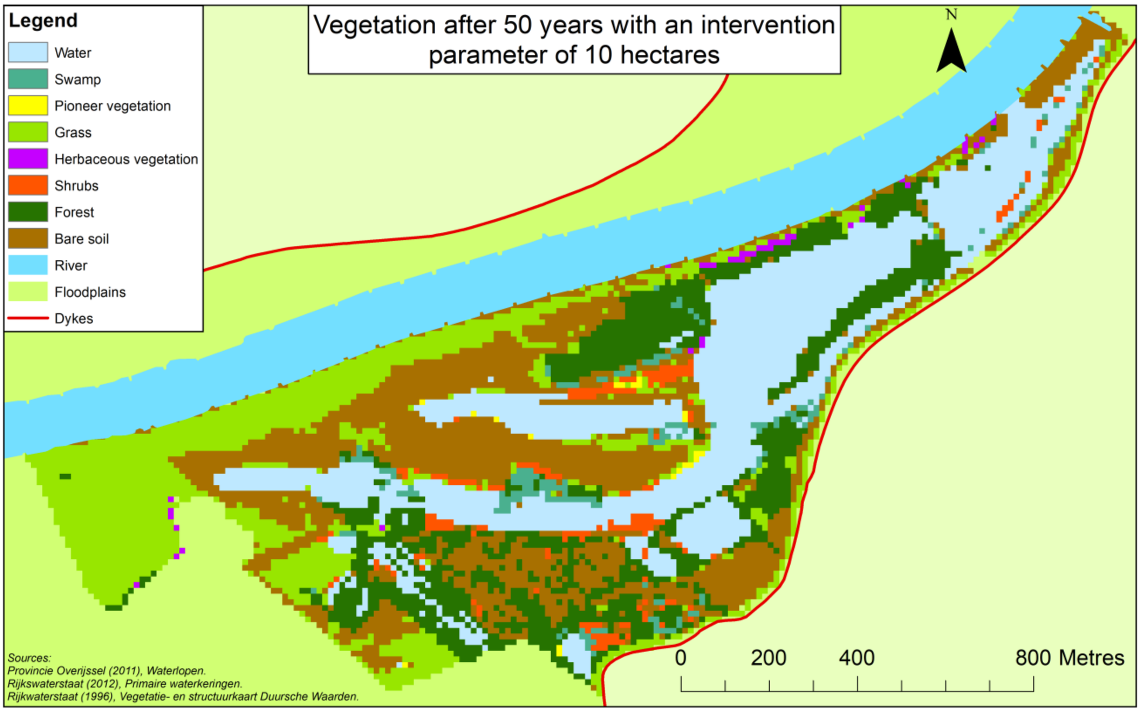
C.6: Vegetation map of the no intervention scenario with double the water level.



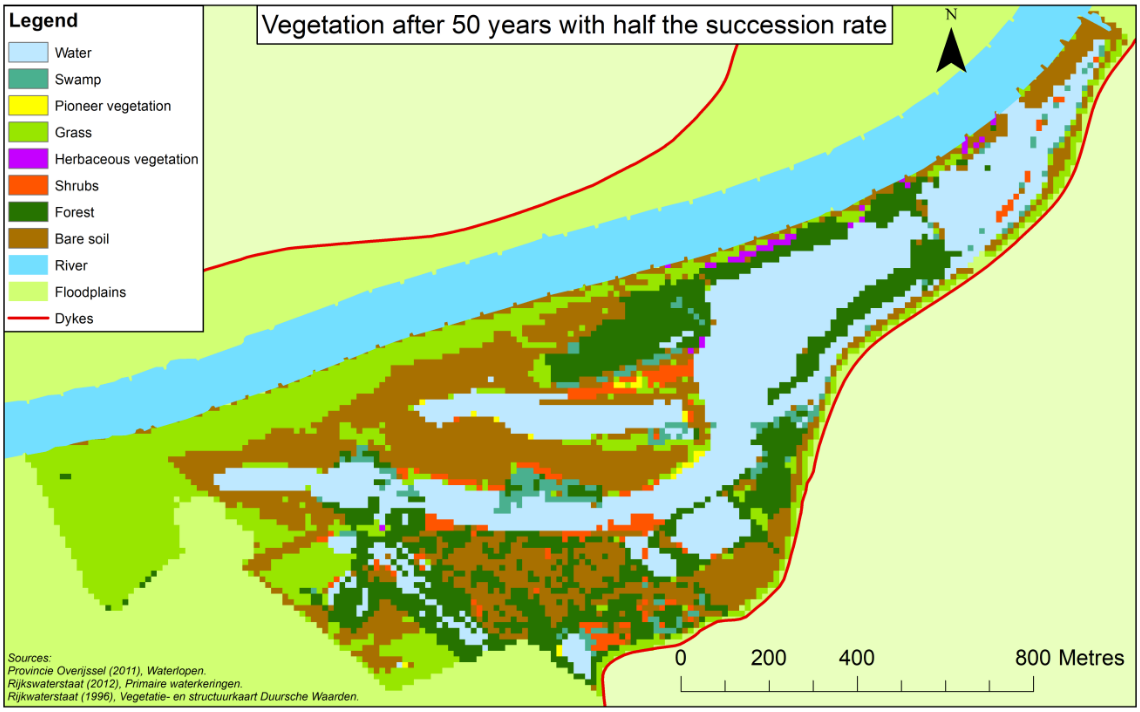
C.7: Vegetation map of the 7 hectares intervention parameter scenario.



C.8: Vegetation map of the 10 hectares intervention parameter scenario.



C.9: Vegetation map of the half succession rate scenario.



C.10: Vegetation map of the double succession rate scenario.